Origins of Hidden Sector Dark Matter

Gilly Elor

290E 10/26/2011

With Clifford Cheung, Lawrence Hall and Piyush Kumar

Cosmology arXiv:1010.0022

Collider Signals arXiv:1010.0024

I. Cosmology

Evidence for Dark Matter

Lots of experimental evidence for the existence of dark matter particles

- Galactic Rotation Curves
- Velocity Dispersions of Galaxies
- Gravitational Lensing
- CMB
- Structure Formation
- ...

Relic abundance measured:

$$\Omega_{DM} h^2 \sim 0.11$$

Production Mechanism?
Candidate which gives correct relic abundance?

Production by “Freeze-Out”

Interactions with Standard Model particles keeps the Dark Matter in thermal equilibrium with the early universe bath as long as the interaction rate exceeds the expansion rate.

$$H(T) < n(T)\langle\sigma v\rangle$$

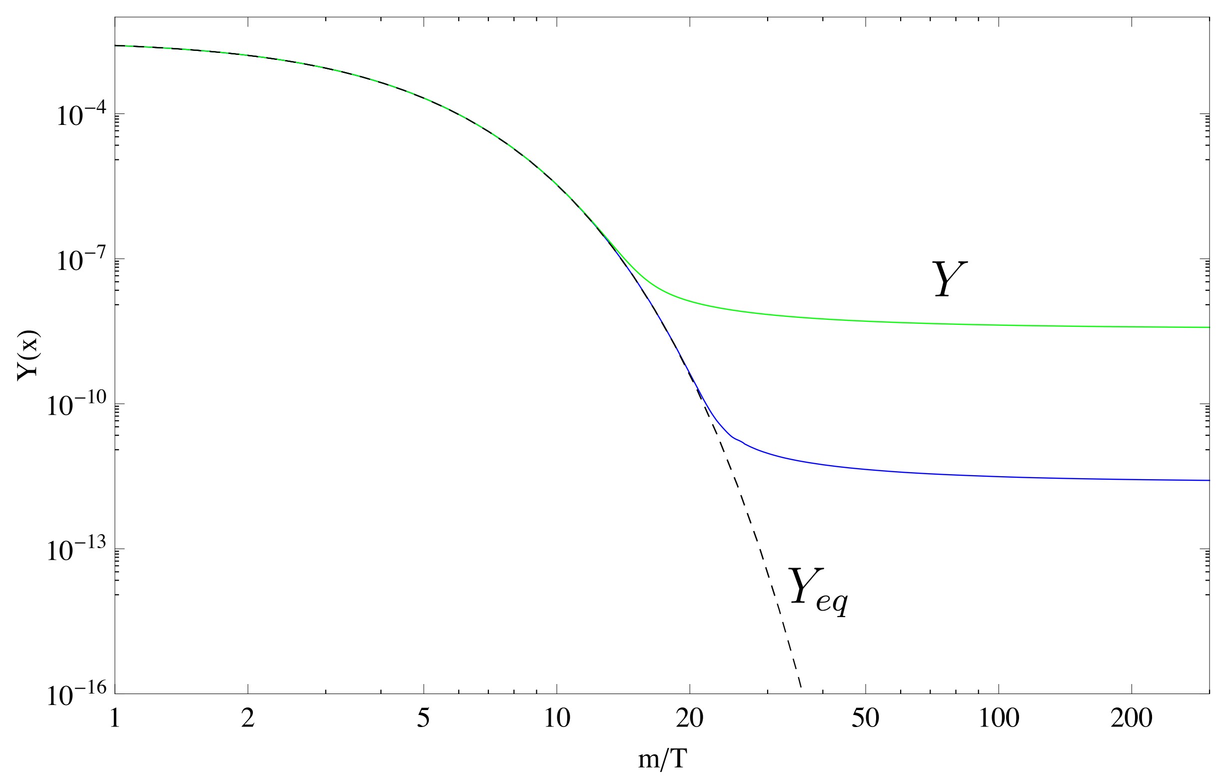
Visible Sector+DM Bath T

The evolution of the number density is given by the Boltzmann equation:

$$\frac{d}{dt}n + 3Hn \quad = \quad -(n^2 - n_{\rm eq}^2)\langle\sigma v\rangle$$

Convention is to re-write in terms of co-moving number density (or Yield): $Y = n/s \qquad x = m/T$

$$\frac{dY}{dx} = -\frac{s\langle\sigma v\rangle}{Hx}\left(Y^2 - Y_{eq}^2\right)$$



Boltz suppression because for a massive particle is becomes hard to produce a particle anti-particle from the bath once the Temperature falls below the mass

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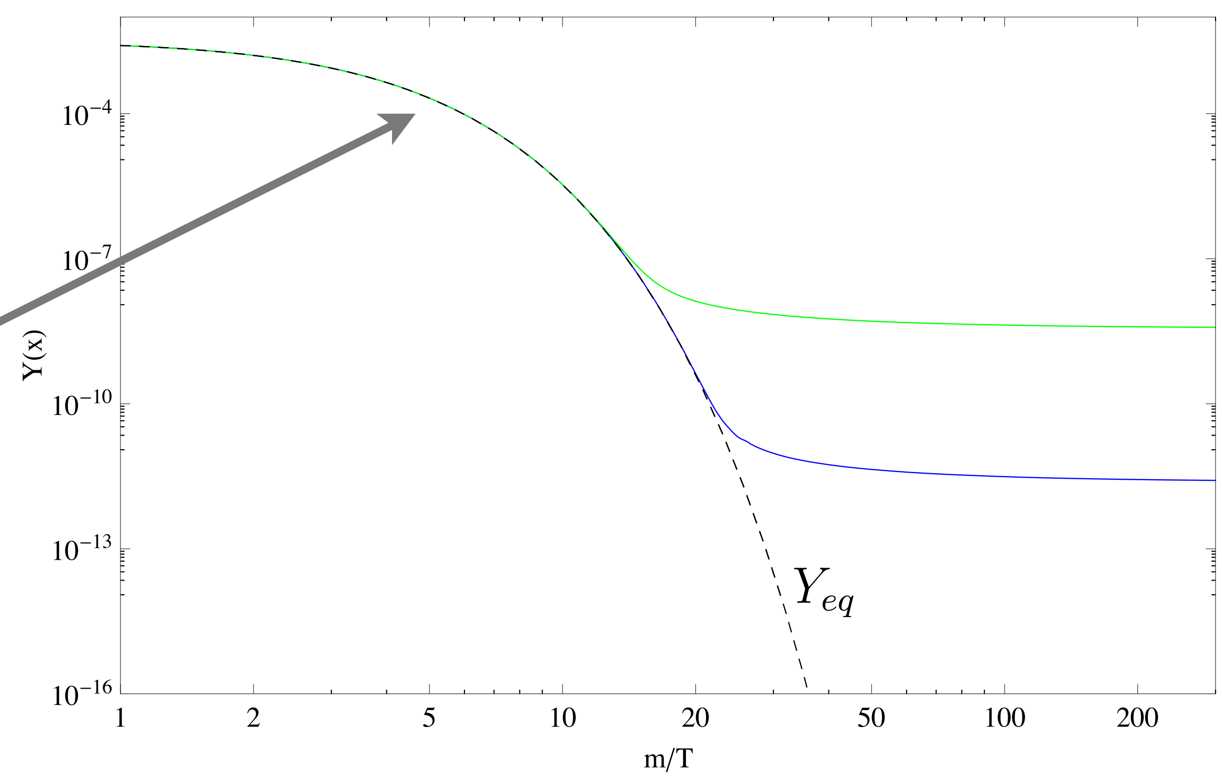
Yield tracks equilibrium value at high T



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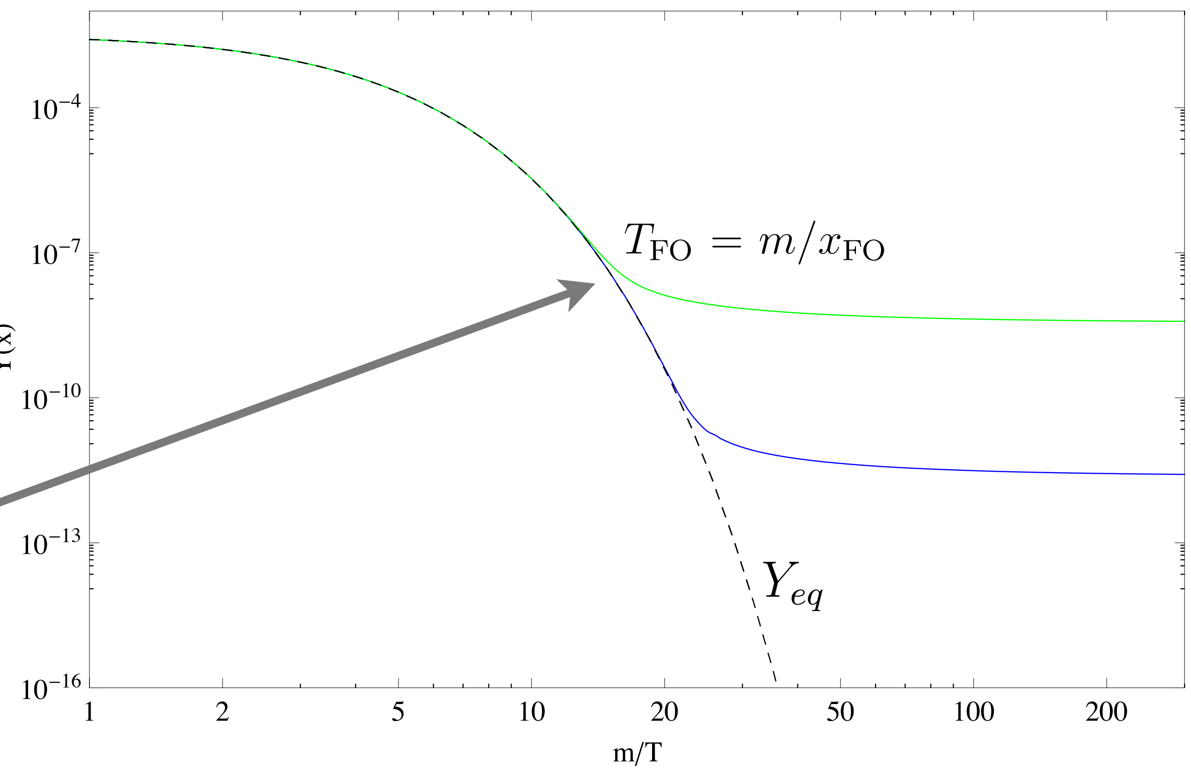
Decoupling

$H(T) \sim n(T)\langle\sigma v\rangle$



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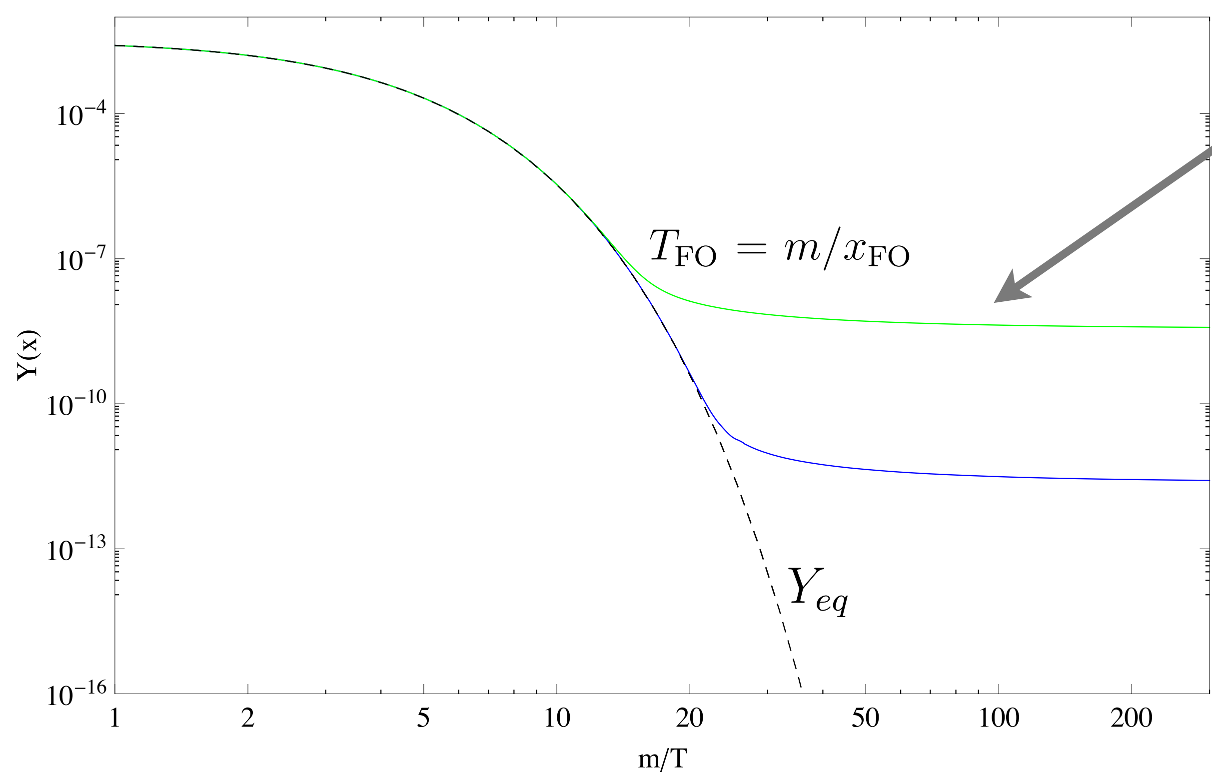

$H > Y(T)s(T)\langle \sigma v \rangle$

$\Rightarrow \quad \frac{dY}{dx} \sim 0$

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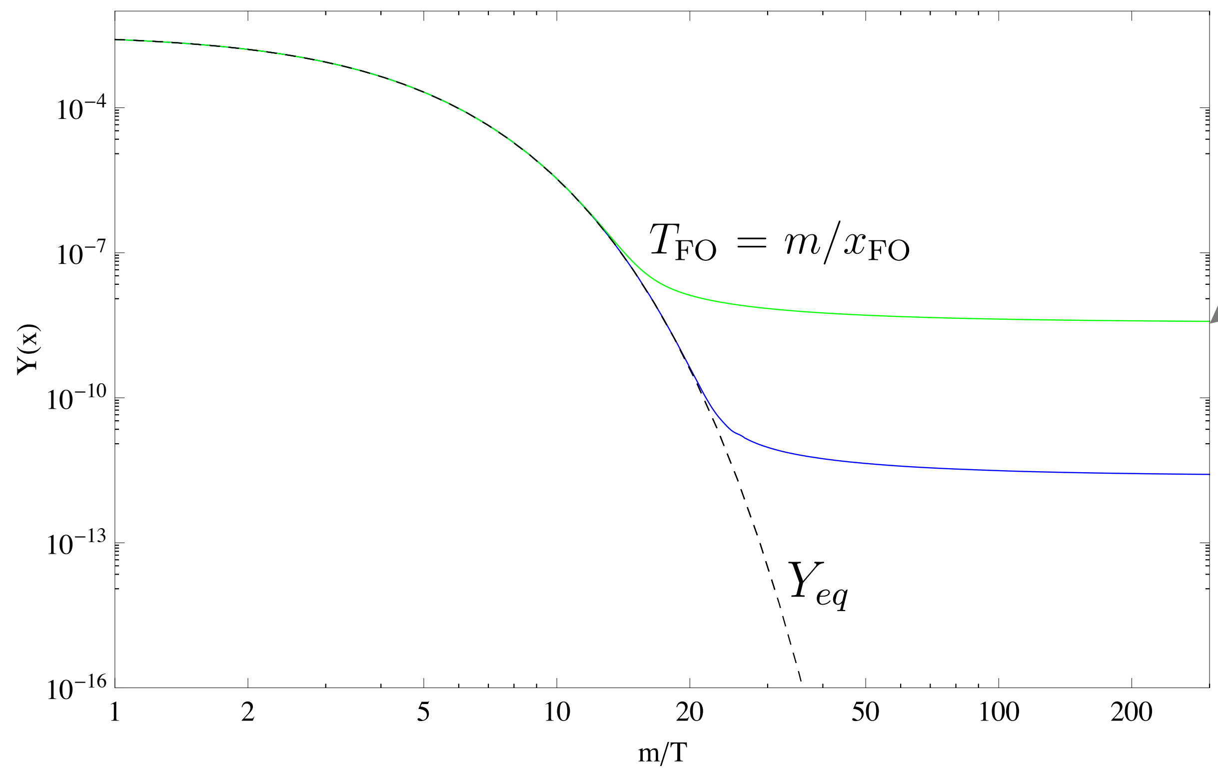

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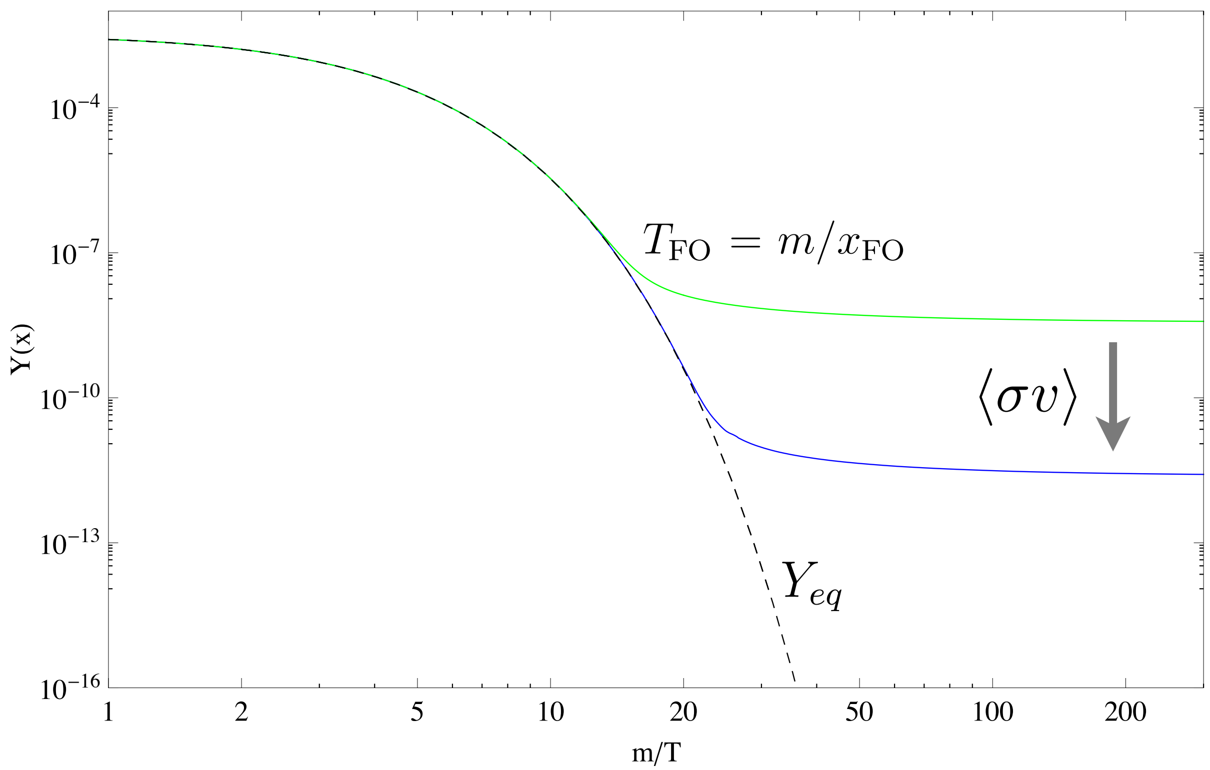

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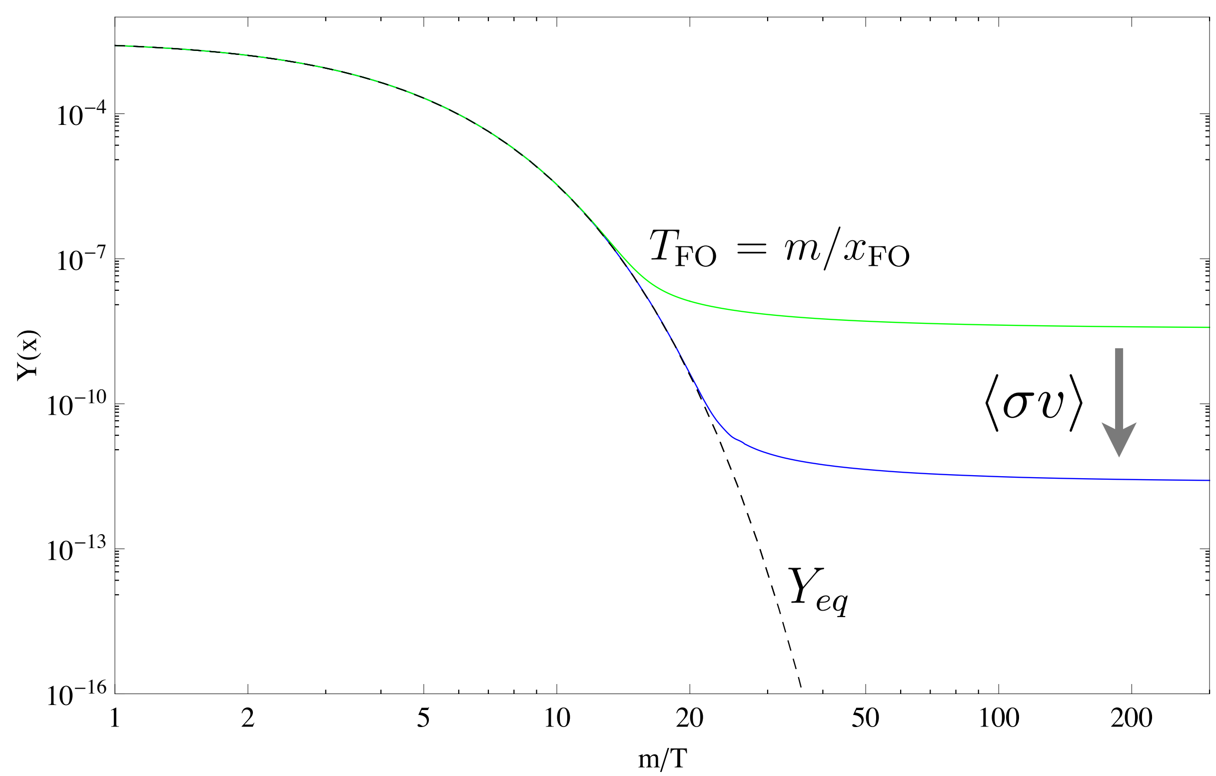

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Dependent only on quantities that can in principle be measured.

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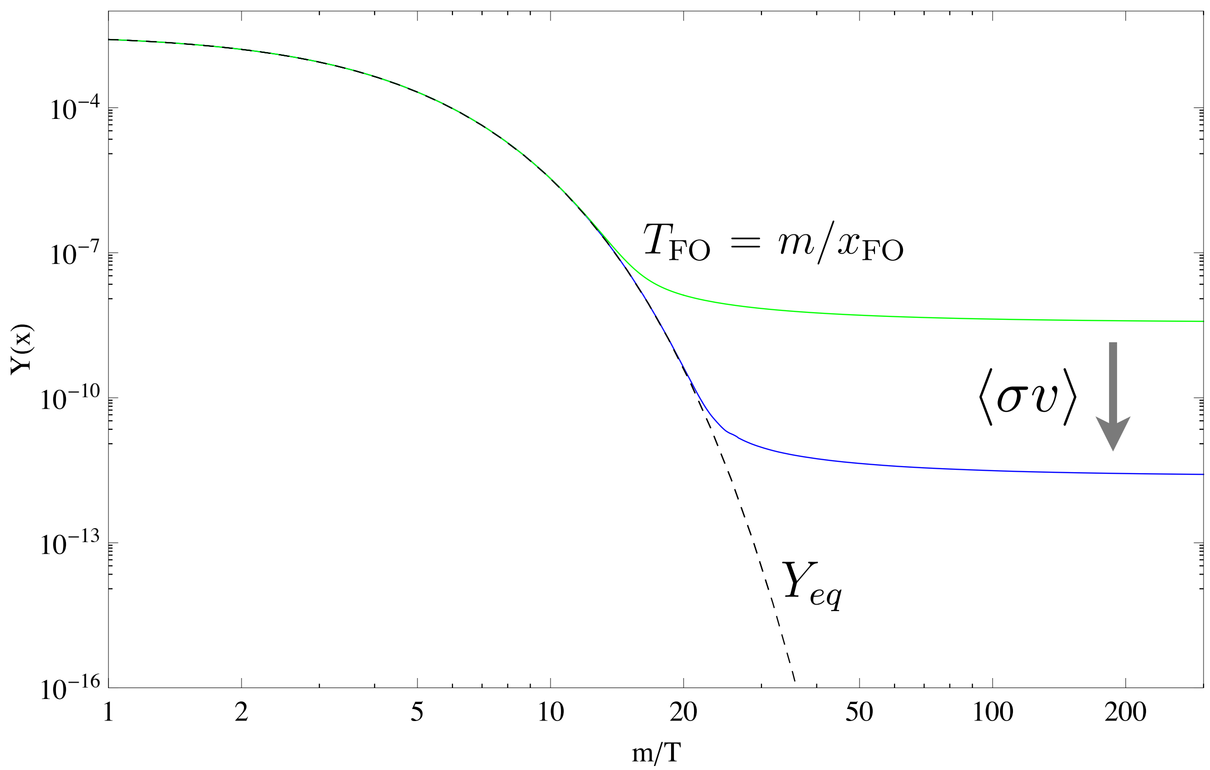
$$mY_{\rm FO} \simeq 4\times10^{-10}\ {\rm GeV}$$



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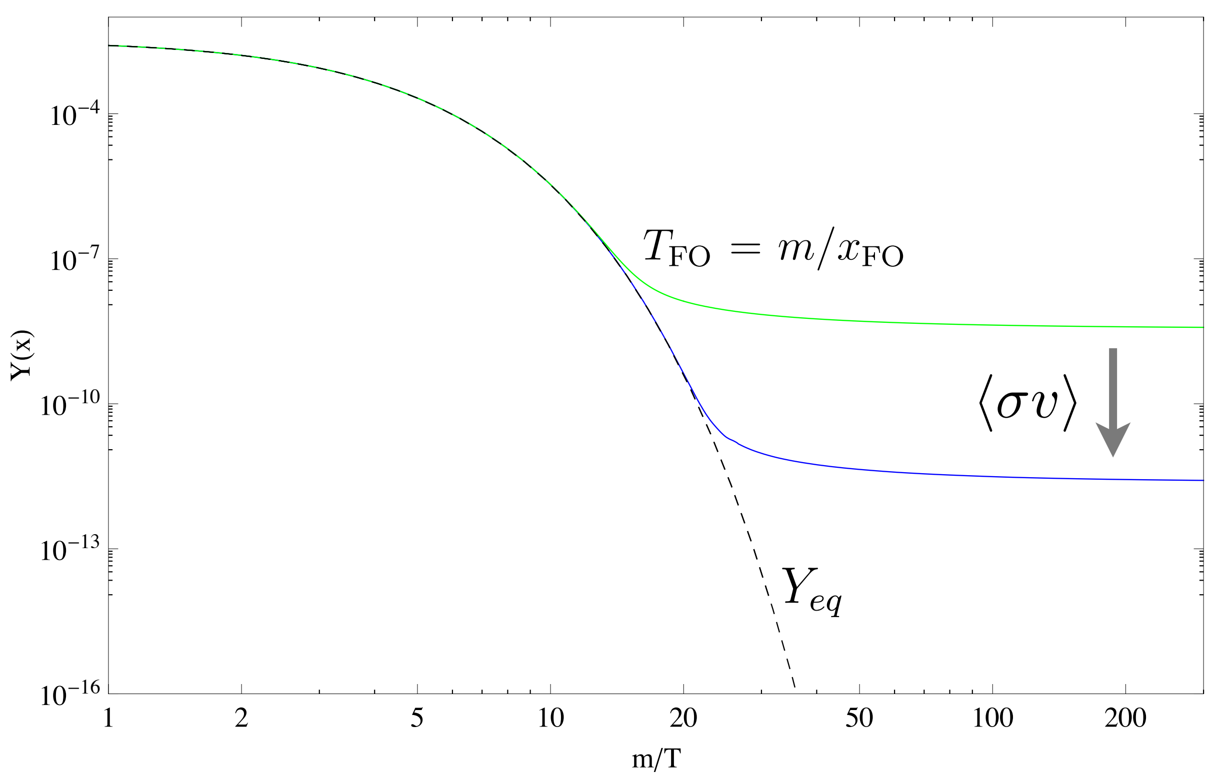

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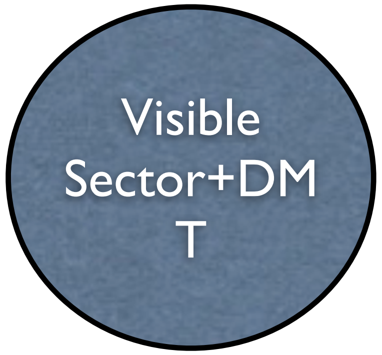

What if Dark Matter is initially decoupled from the thermal bath?

[L. Hall, K. Jedamzik, J. March-Russel, S. West arXiv:0911.1120]

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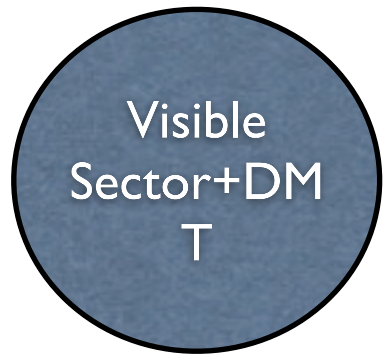

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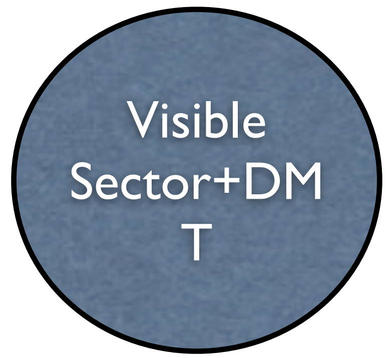

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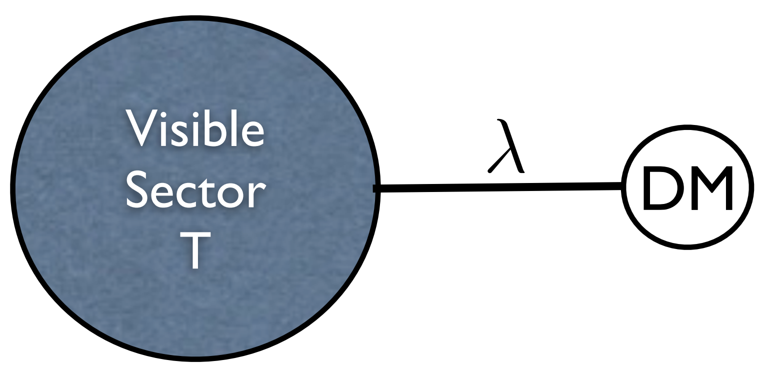

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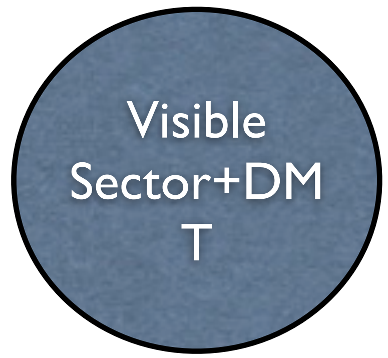

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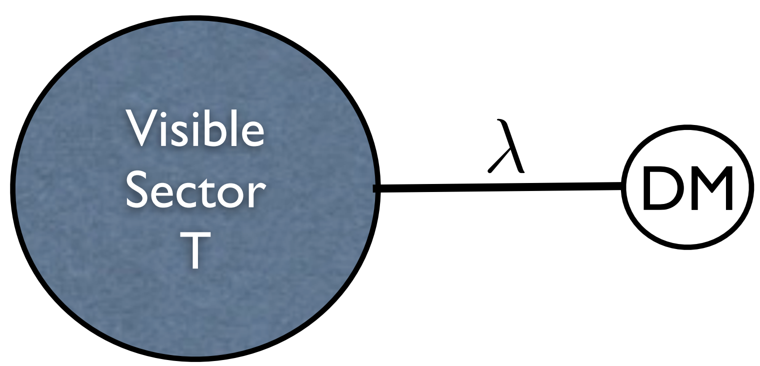

Feeble interaction allows for a new production mechanism:

Freeze-In

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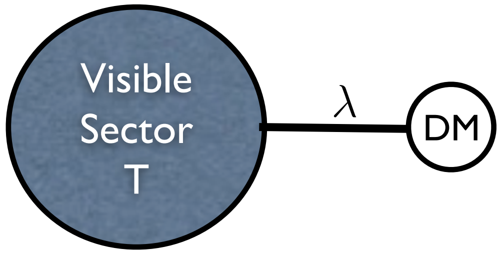
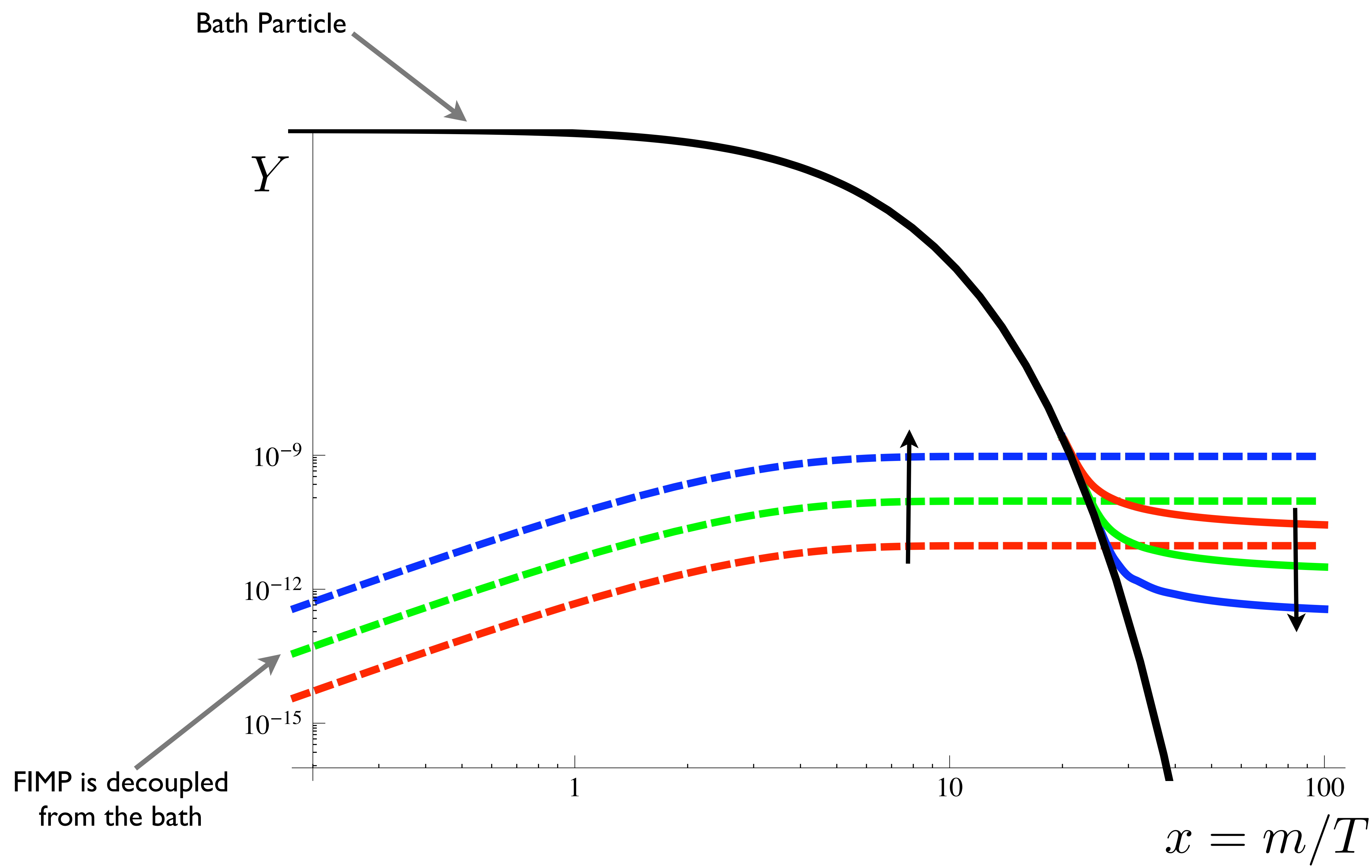
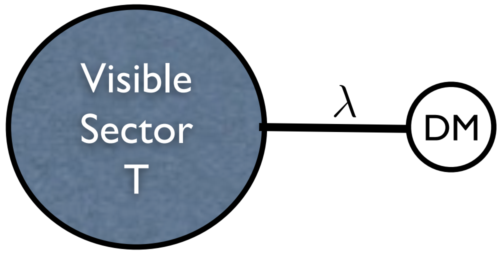


Visible
Sector
T
λ
DM



Bath Particle
Y
10^{-9}
10^{-12}
10^{-15}
1
10
100
$x = m/T$
FIMP is decoupled
from the bath

Freeze-In


Visible
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T
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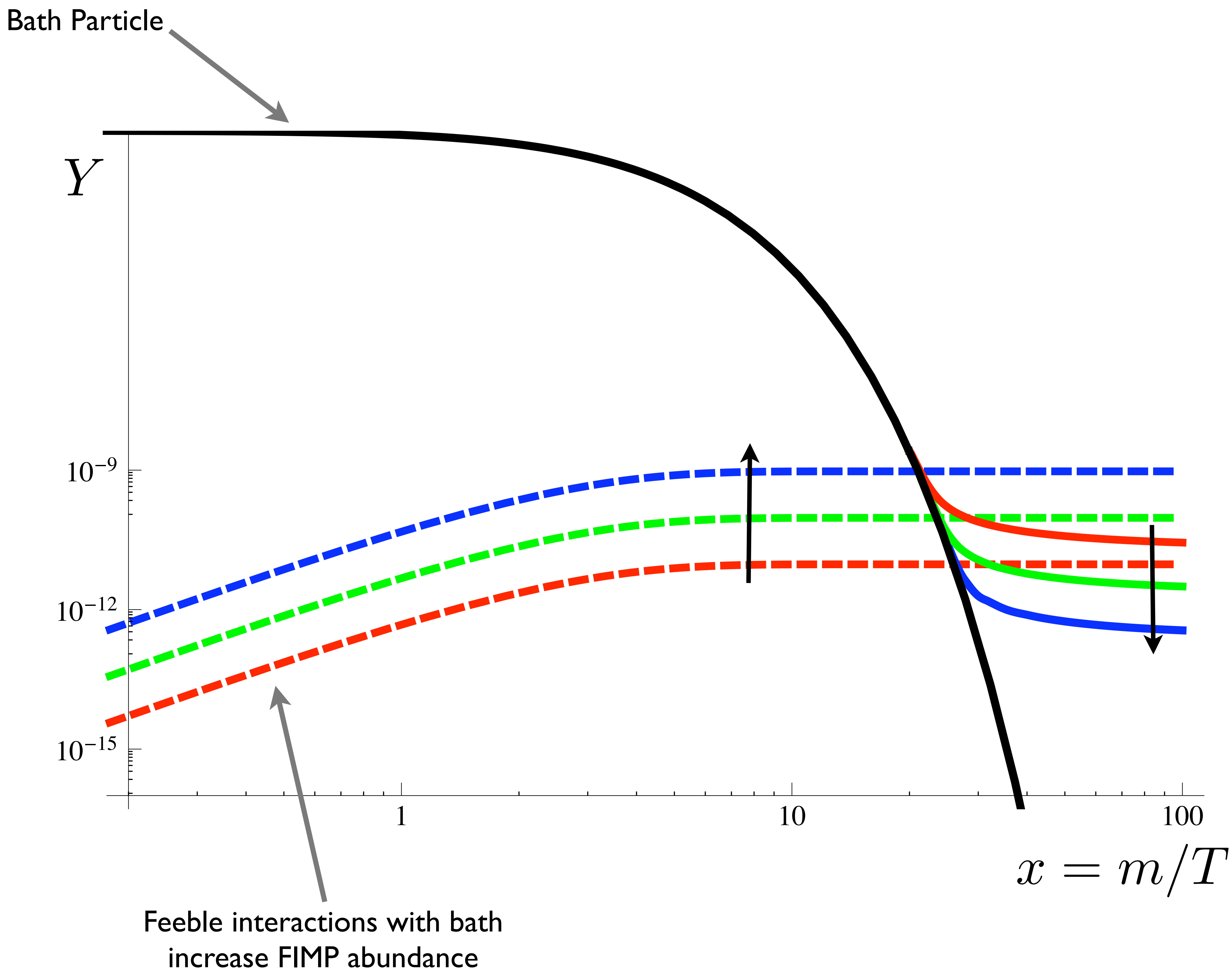
Bath Particle
Y
10^{-9}
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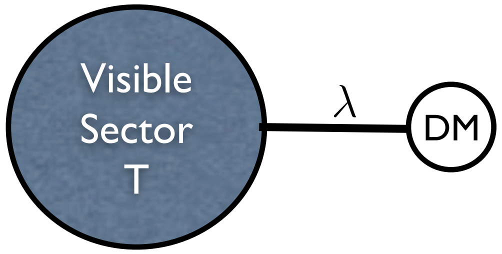
10
100
$x = m/T$
Feeble interactions with bath
increase FIMP abundance

Freeze-In



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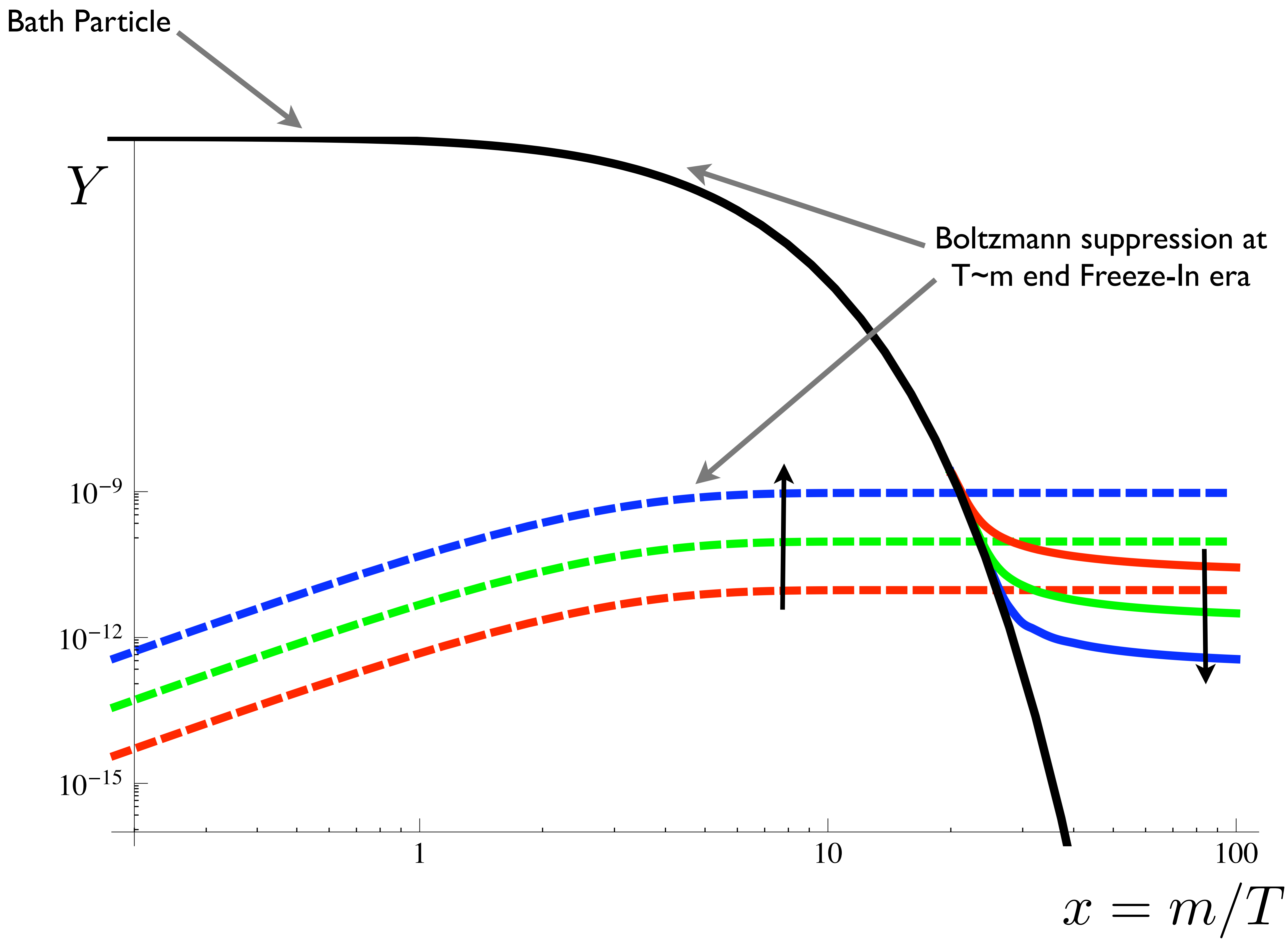
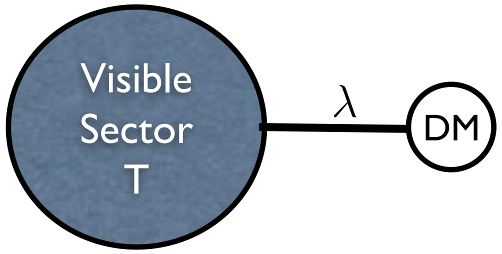
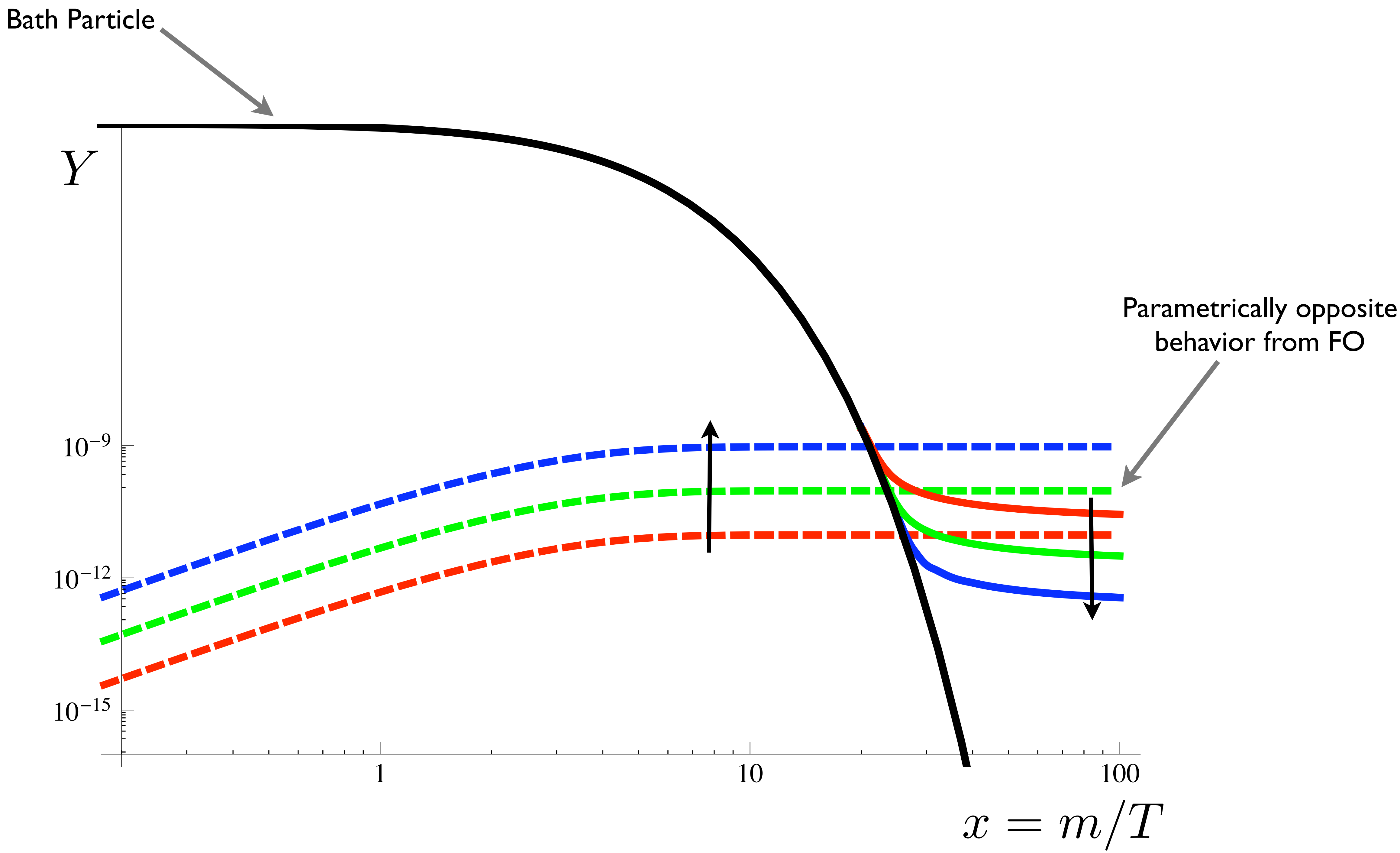


Bath Particle
Boltzmann suppression at
T~m end Freeze-In era
Y
10^{-9}
10^{-12}
10^{-15}
1
10
100
$x = m/T$

Freeze-In

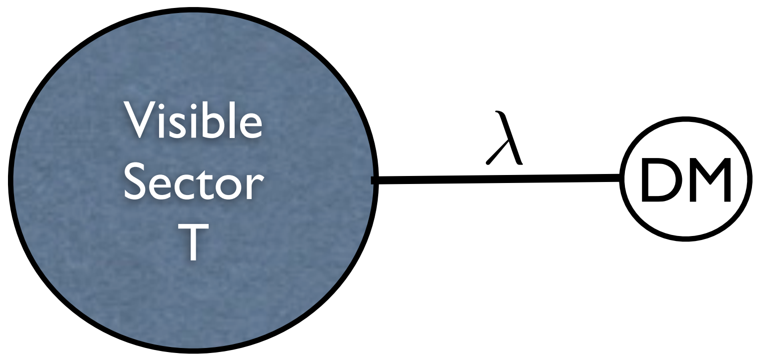


Visible
Sector
T
λ
DM



Bath Particle
Y
10^{-9}
10^{-12}
10^{-15}
1
10
100
$x = m/T$
Parametrically opposite
behavior from FO

An Obvious Extension



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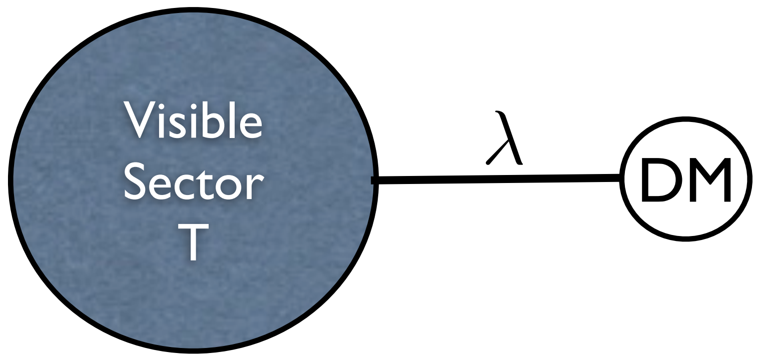

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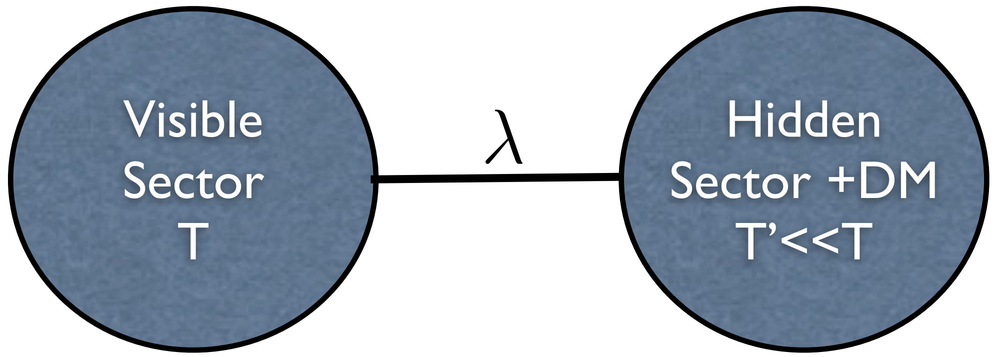

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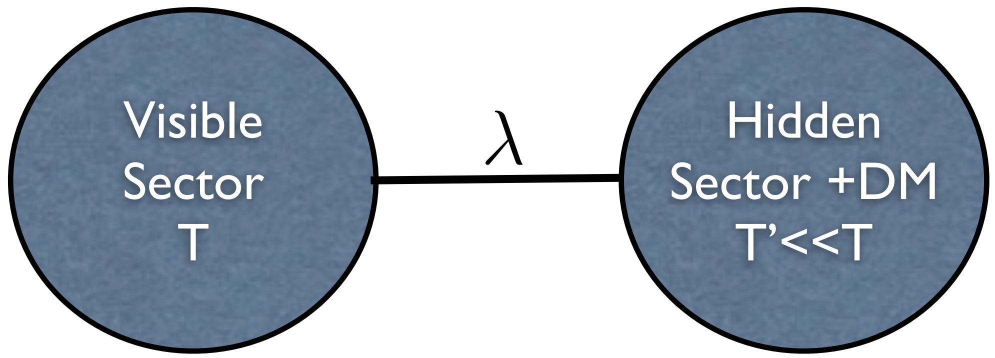

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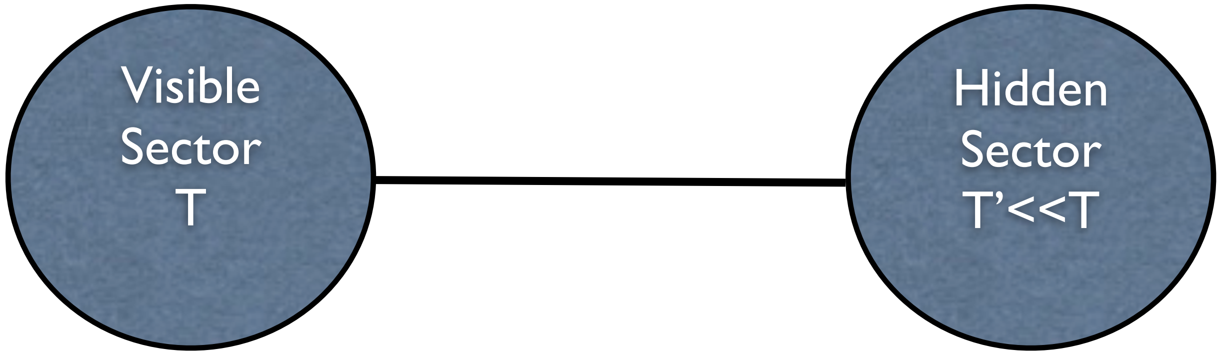
What are the possible production mechanisms of "Hidden Sector Dark Matter"

Cosmology arXiv:1010.0022

Hidden Sector Dark Matter

A General Set Up:



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- Each sector contains its own self interactions sufficient to maintain thermal equilibrium

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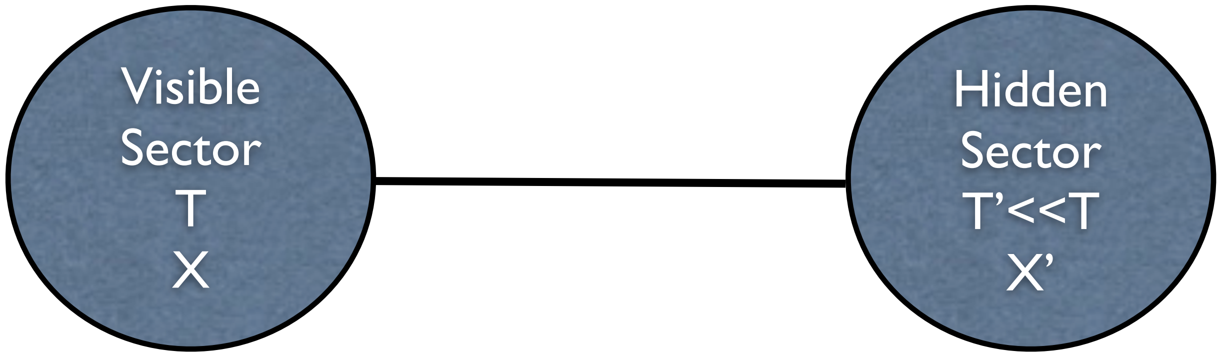

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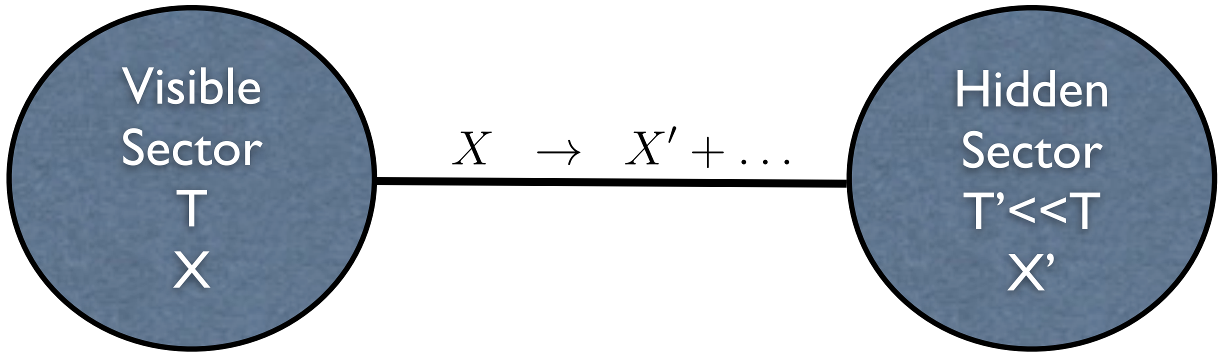

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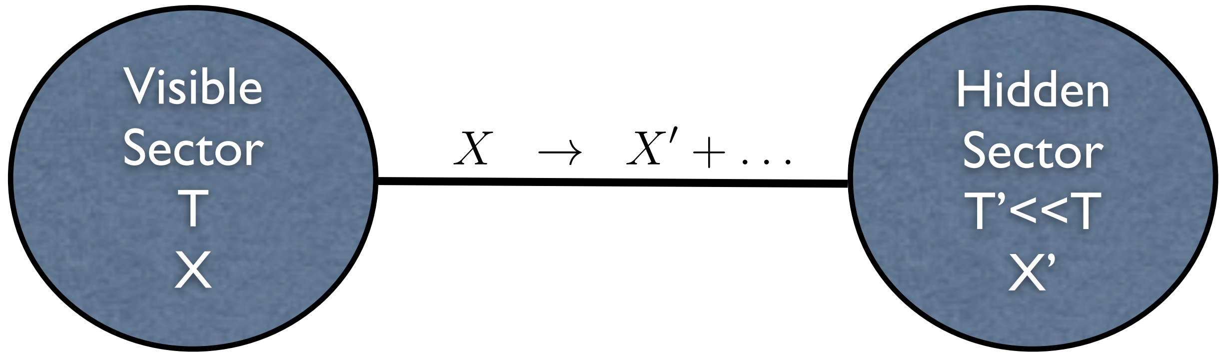
- Each sector contains its own self interactions sufficient to maintain thermal equilibrium
- There exists a stabilizing symmetry. Take X/X' to be the lightest particle in the visible/hidden sector charged under the stabilizing symmetry. $m > m'$
- There exists a small coupling between the two sectors mediating the decay $X \rightarrow X' + \ldots$

Hidden Sector Dark Matter

A General Set Up:



$$\xi \equiv \frac{T'}{T}.$$

- Each sector contains its own self interactions sufficient to maintain thermal equilibrium

- There exists a stabilizing symmetry. Take X/X' to be the lightest particle in the visible/hidden sector charged under the stabilizing symmetry. $m > m'$

- There exists a small coupling between the two sectors mediating the decay $X \rightarrow X' + \ldots$

- Coupled Boltzmann equations:

$$\begin{aligned} \frac{d}{dt}n + 3Hn &= -(n^2 - n_{\rm eq}^2)\langle \sigma v \rangle - \Gamma n \\ \frac{d}{dt}n' + 3Hn' &= -(n'^2 - n'^2_{\rm eq})\langle \sigma v \rangle' + \Gamma n, \end{aligned}$$

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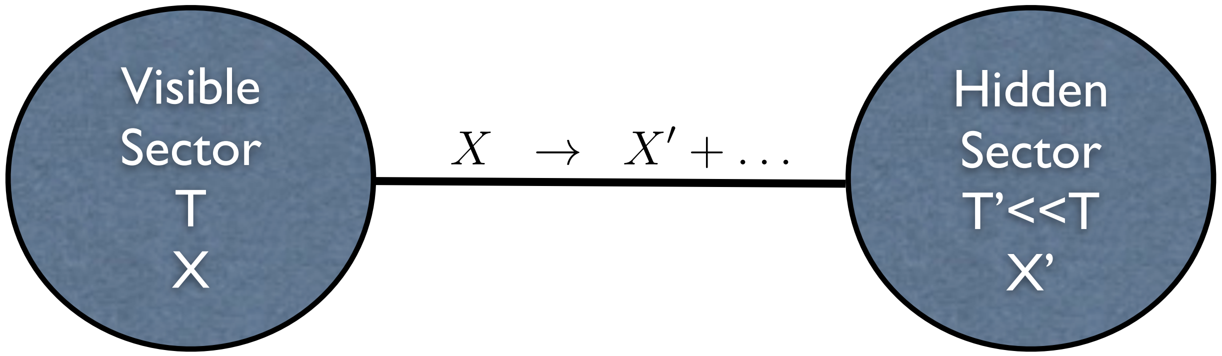

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Scattering of X in visible bath

$$\begin{aligned} \frac{d}{dt}n + 3Hn &= -(n^2 - n_{\rm eq}^2)\langle \sigma v\rangle - \Gamma n \\ \frac{d}{dt}n' + 3Hn' &= -(n'^2 - n'^2_{\rm eq})\langle \sigma v\rangle' + \Gamma n, \end{aligned}$$

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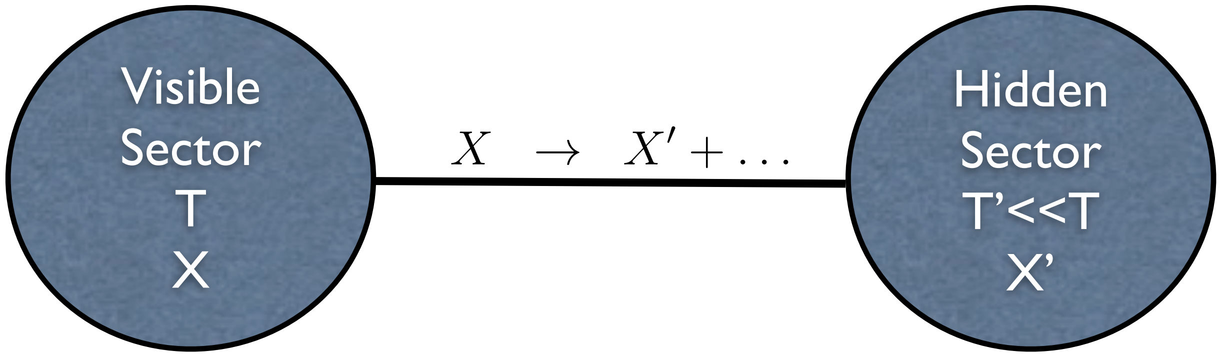

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\end{aligned}$$

Scattering of X' in hidden bath

Hidden Sector Dark Matter

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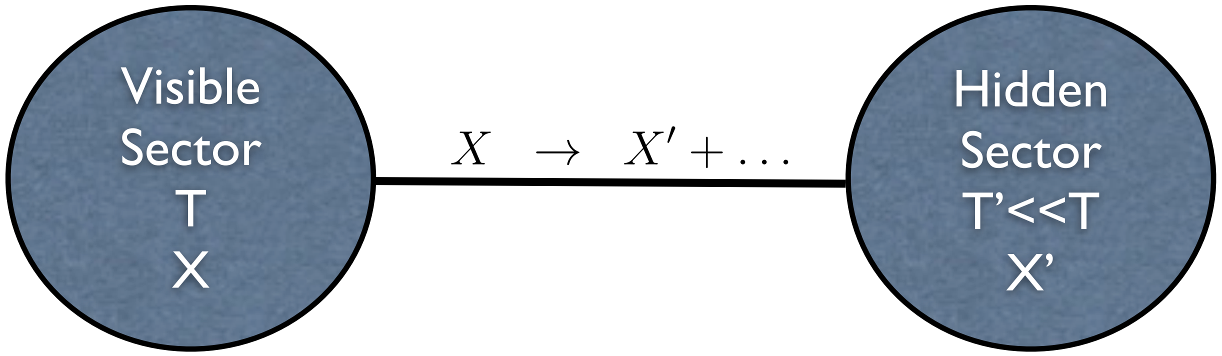

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Decay rate of X to X'
~ free parameter

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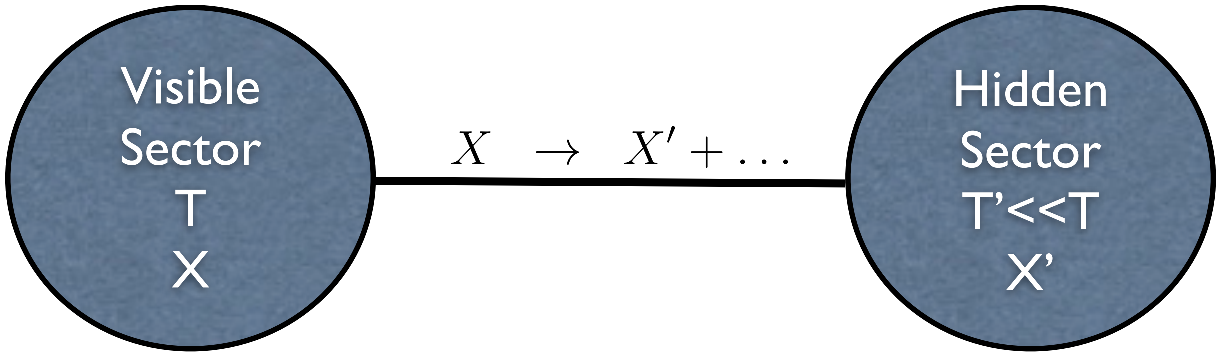

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- Seven dimensional parameter space:

$$\{m, m', \langle\sigma v\rangle, \langle\sigma v\rangle', \xi, \tau, \epsilon\}$$

Two-Sector Cosmology

- Identify reconstructable Dark Matter production mechanisms.

$$\begin{aligned} \frac{d}{dt}n + 3Hn &= -(n^2 - n_{\rm eq}^2)\langle\sigma v\rangle - \Gamma n \\ \frac{d}{dt}n' + 3Hn' &= -(n'^2 - n'^2_{\rm eq})\langle\sigma v\rangle' + \Gamma n, \end{aligned}$$

- Identify dependance of dominating production mechanism on the parameter space.

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Not entirely independent

Interactions between the two sectors change hidden sector temperature

Initial condition: $\xi_{\rm inf} = T'_{\rm inf}/T_{\rm inf}$

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UV scattering

$$\xi^4(T) = \xi^4_{\rm UV} + \xi^4_{\rm IR}(T)$$

The free parameter

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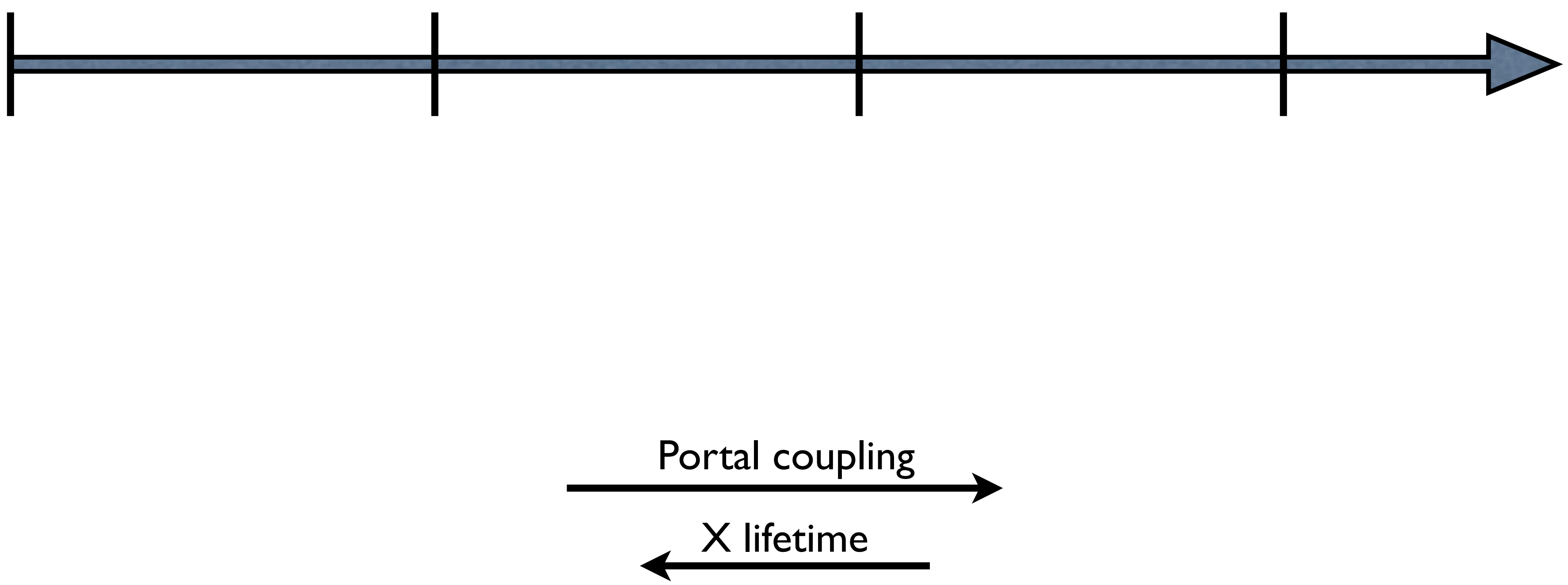
The free parameter Calculable

Two-Sector Cosmology

General behavior can be understood in terms of size of portal coupling



Two-Sector Cosmology

General behavior can be understood in terms of size of portal coupling

Multi-Component: X is stable, sectors fully decoupled, X and X' comprise DM via FO and FO'

Portal coupling →

← X lifetime

Two-Sector Cosmology

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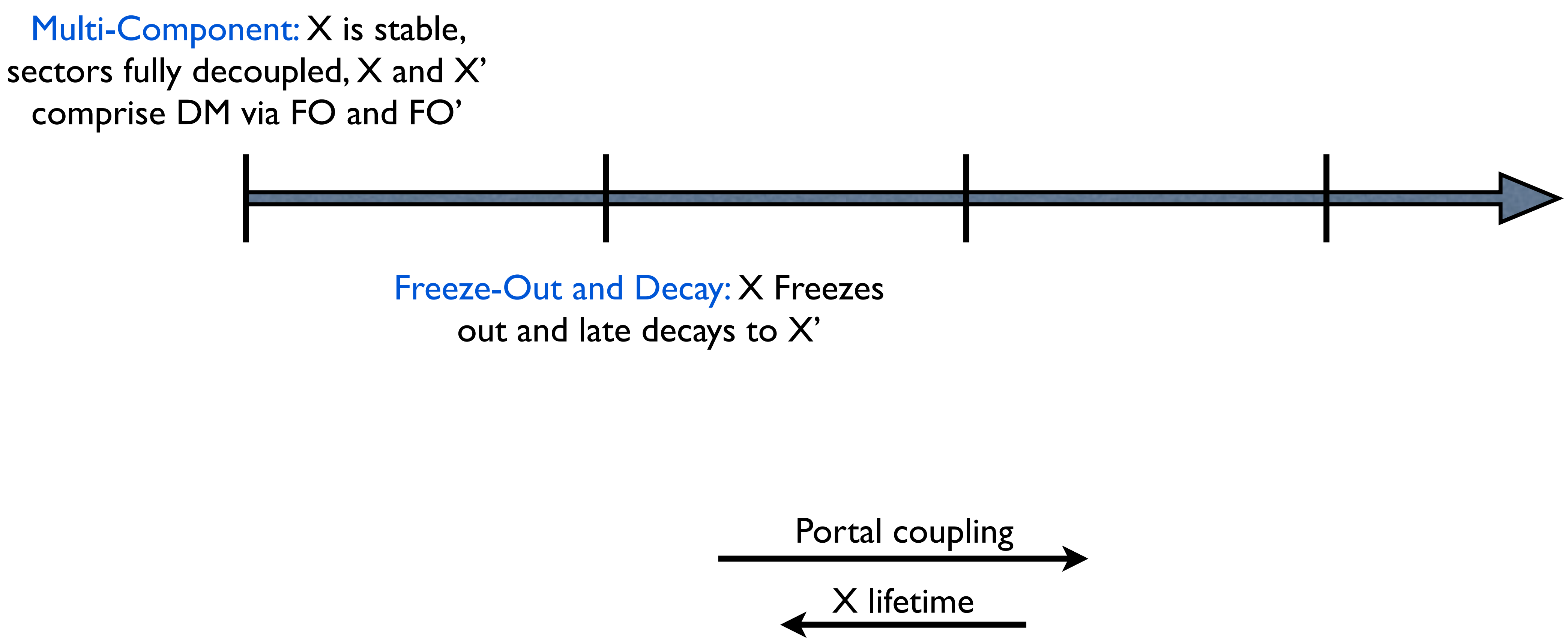

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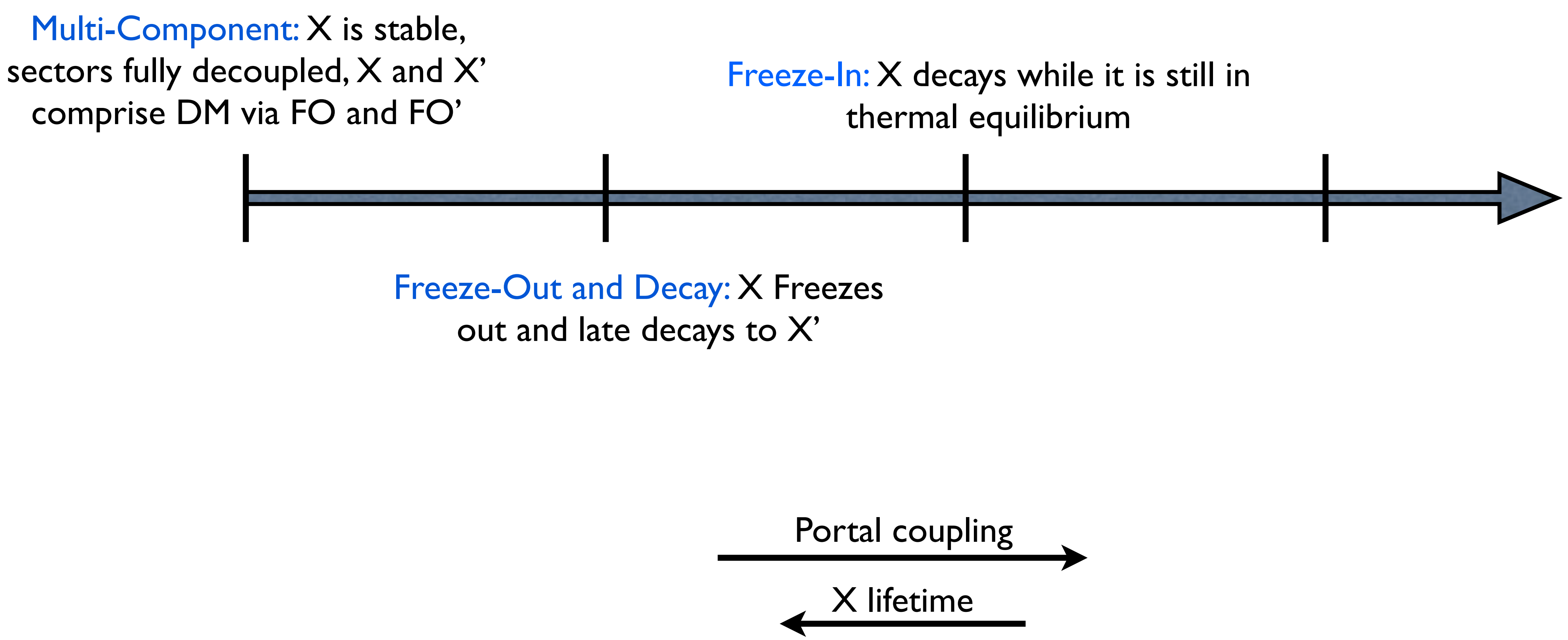

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Freeze-In: X decays while it is still in thermal equilibrium

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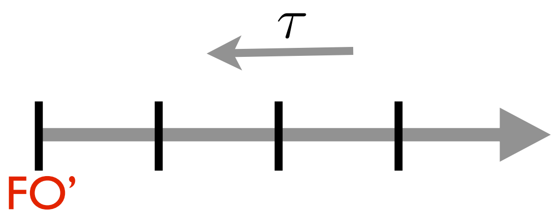
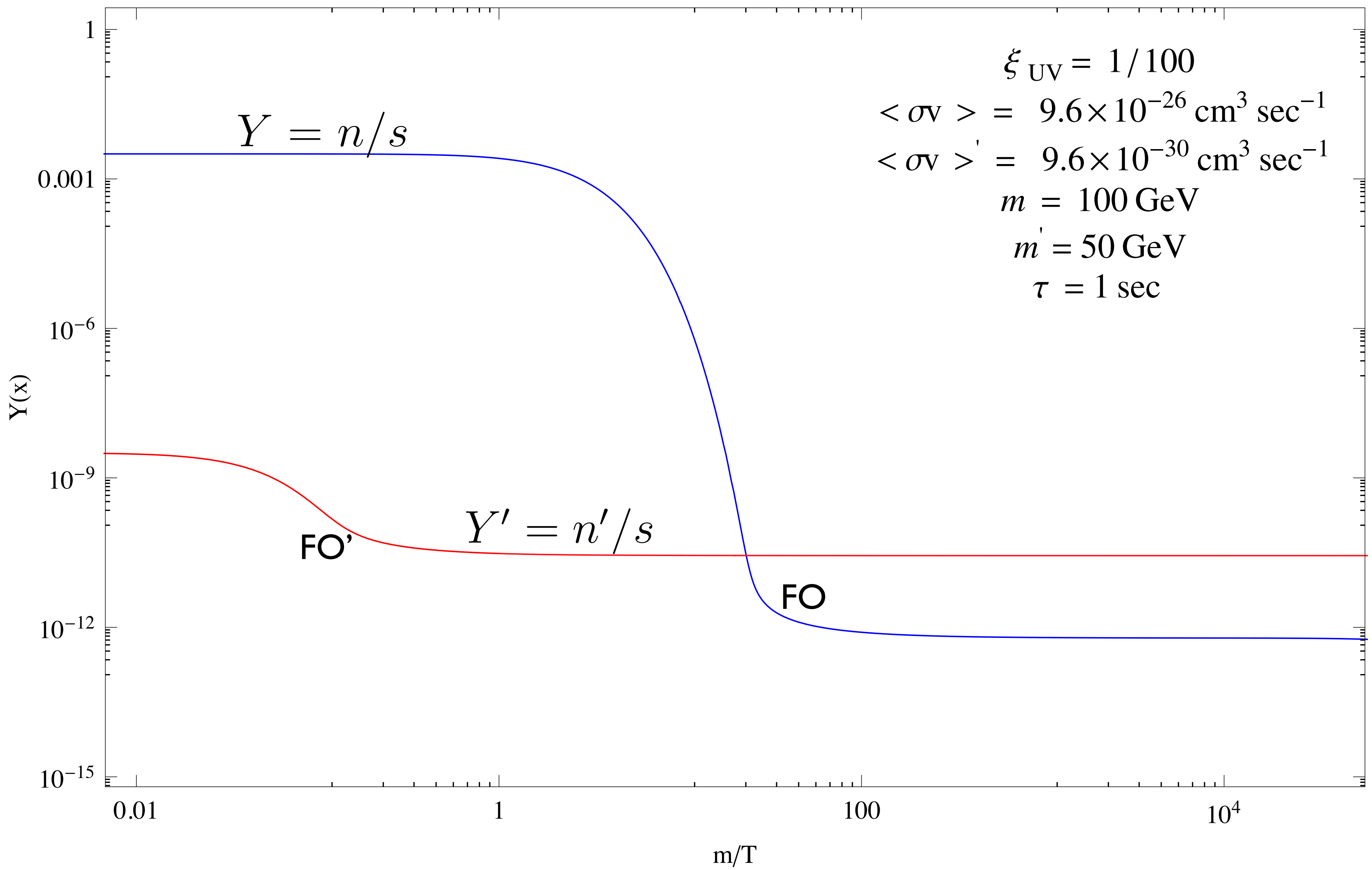
We see this numerically by solving the Boltzmann equations...

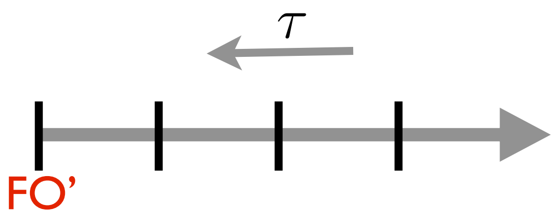


Hidden Sector Freeze-Out

J.L Feng, H.Tu, H.B.Yu hep-ph/0404198



X is very long lived, sectors effectively decoupled



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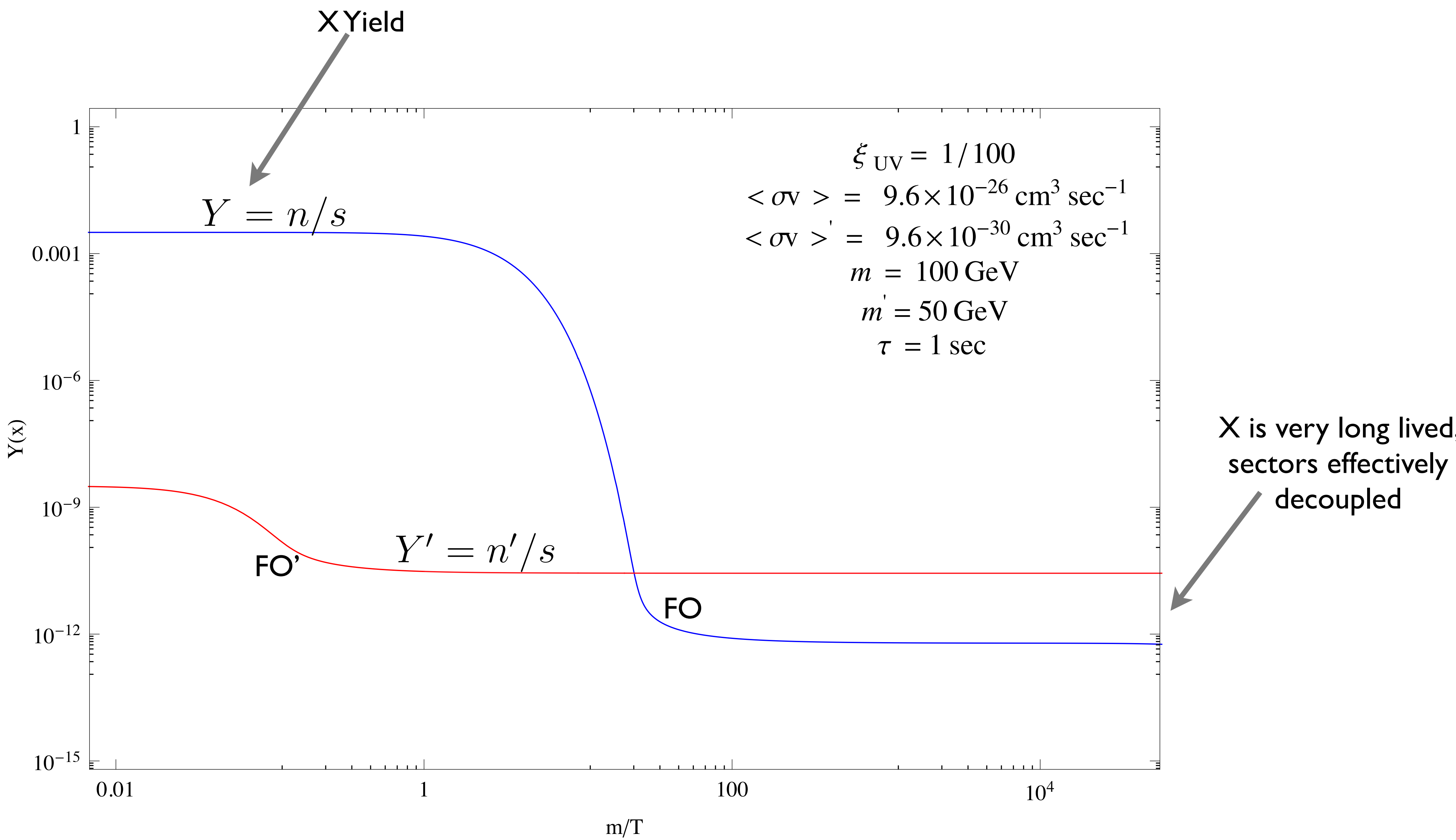

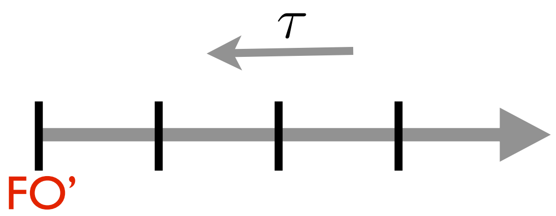

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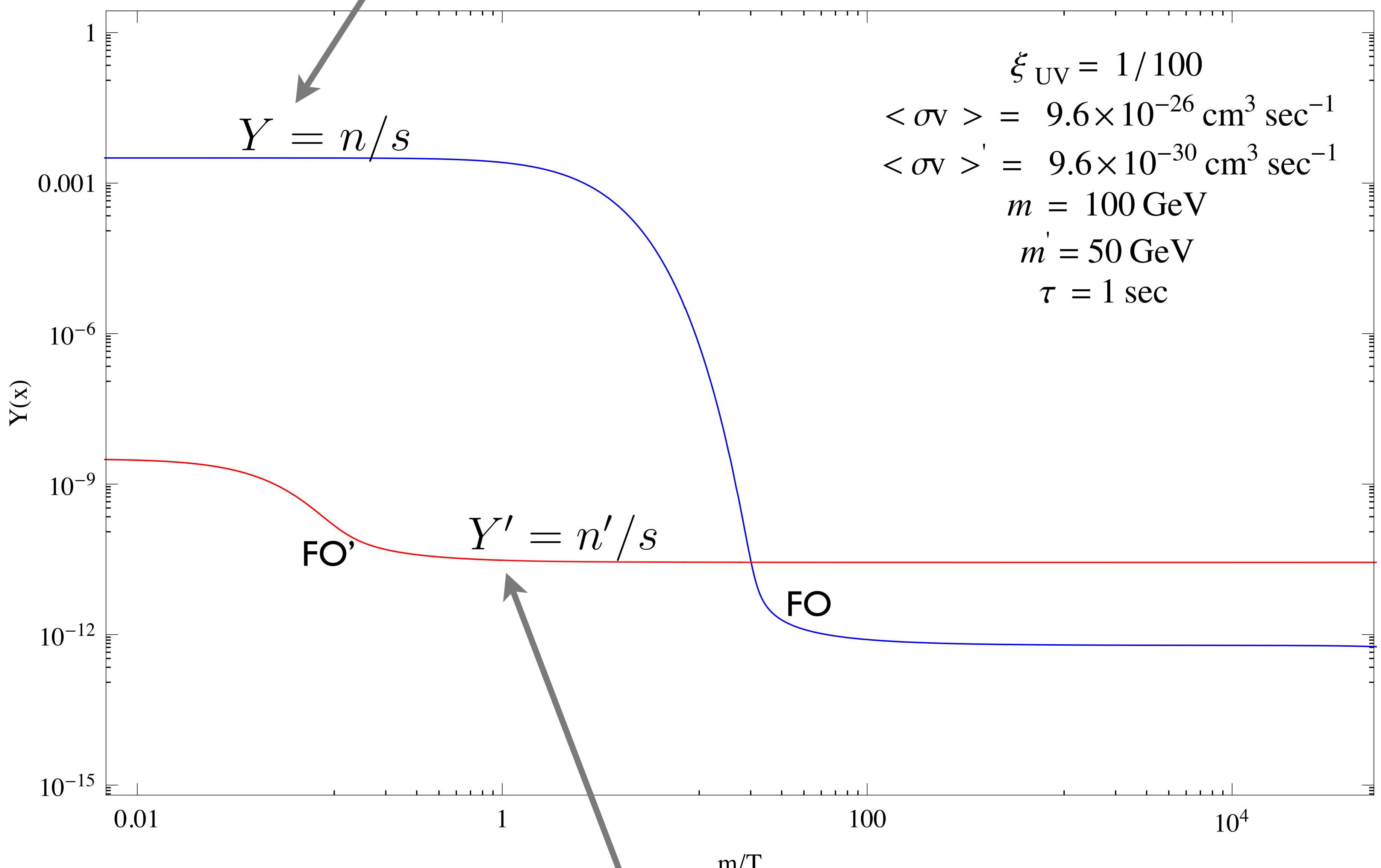
X Yield



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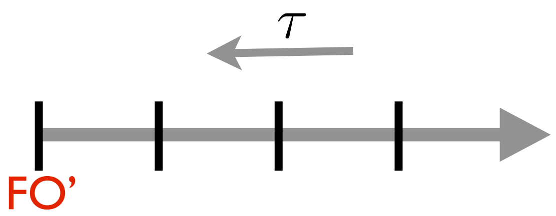
X' Yield in terms of visible sector variables s(T) and m/T



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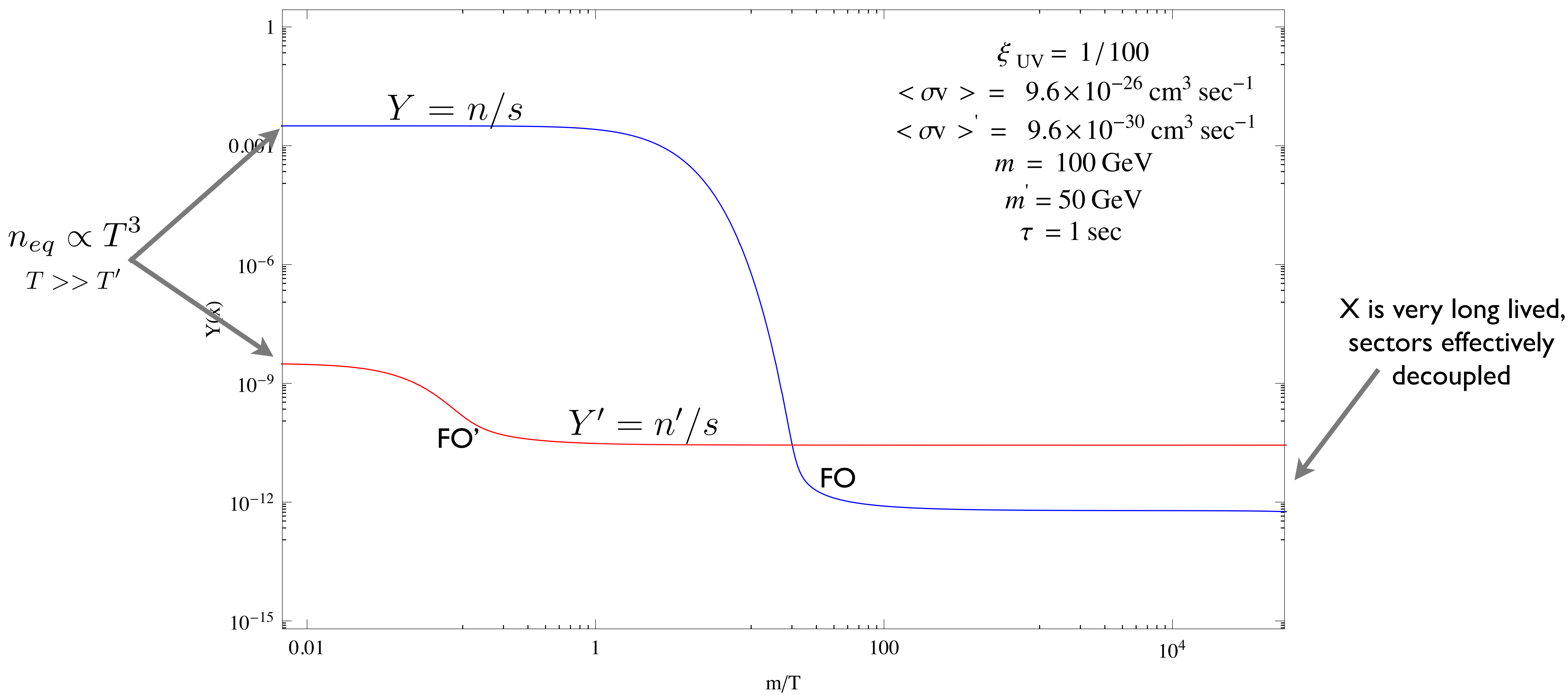

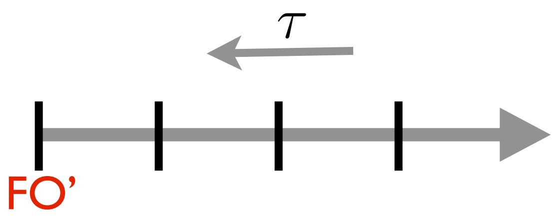

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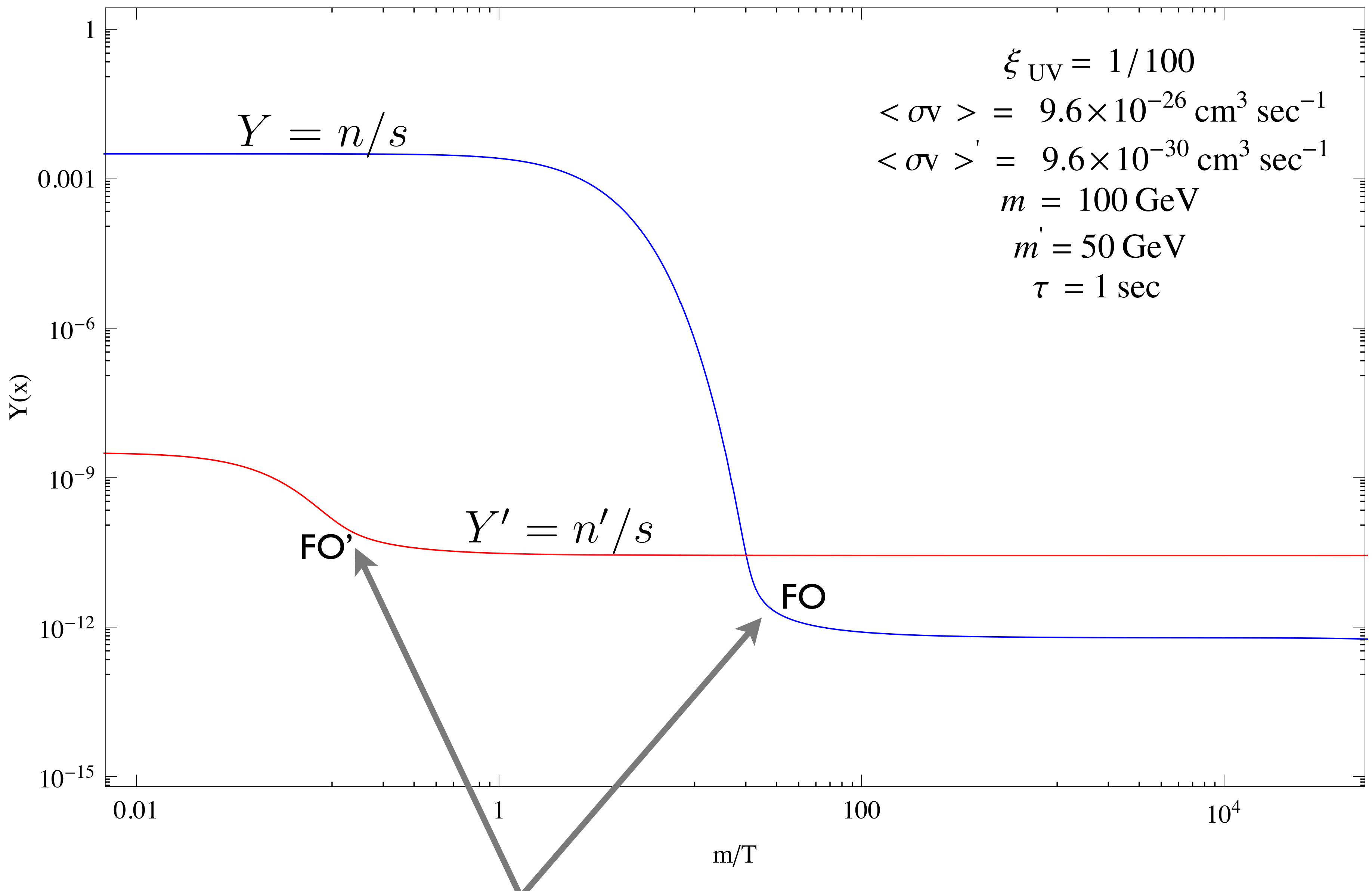
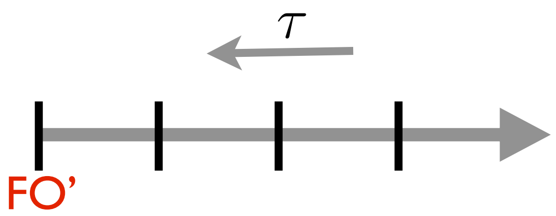


X is very long lived, sectors effectively decoupled

$$\frac{T_{\mathrm{FO'}}}{T_{\mathrm{FO}}} = \frac{1}{\xi_{\mathrm{FO'}}}\frac{m'}{m}$$

Focus on the case where FO' occurs before FO



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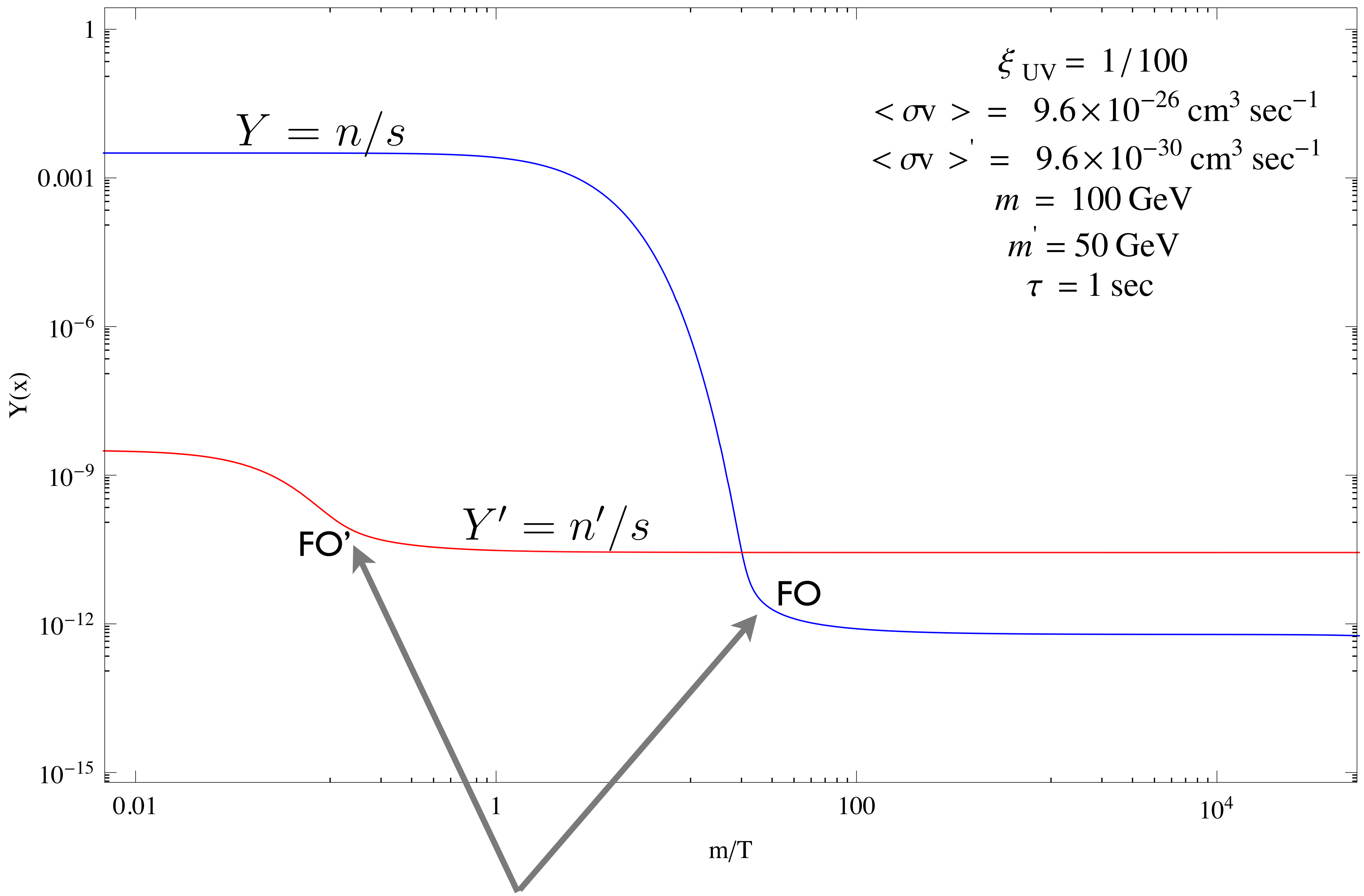
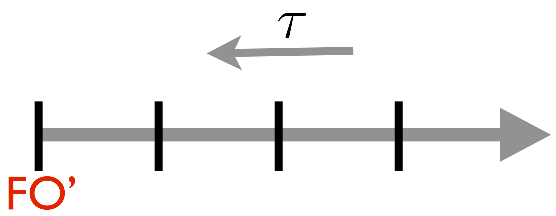


X is very long lived, sectors effectively decoupled

$\langle\sigma v\rangle' << \langle\sigma v\rangle$ Hidden sector interactions not too strong so that FO' dominates over FO



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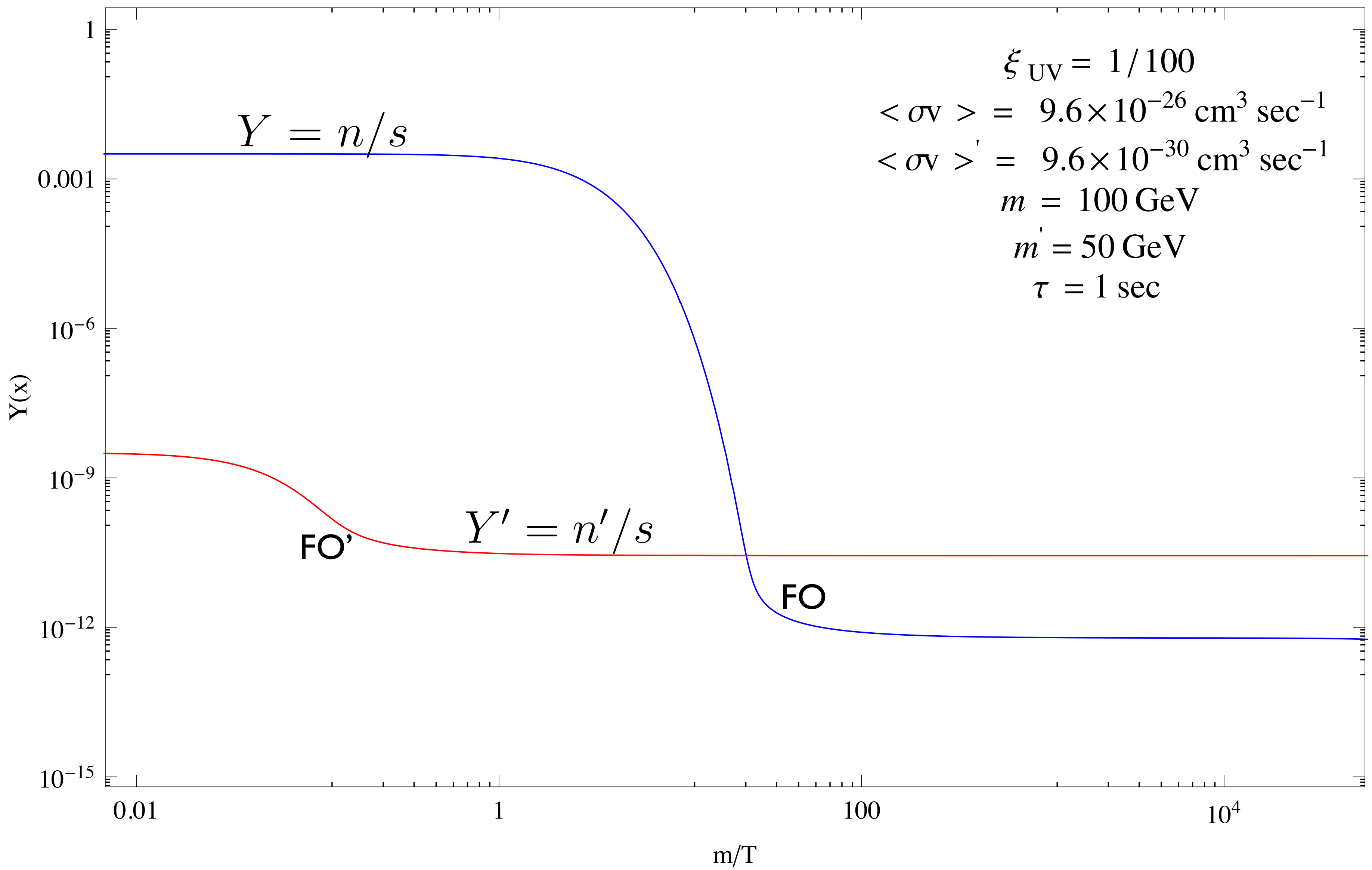
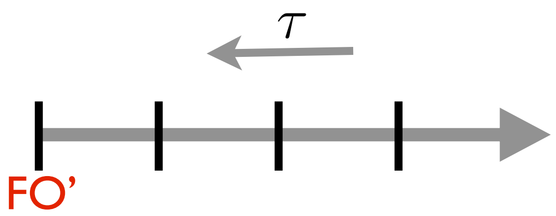


“Freeze out with hidden sector variables”:

$$Y'_{\mathrm{FO'}} \propto \frac{\xi_{\mathrm{FO'}}}{m'\langle\sigma v\rangle'}$$



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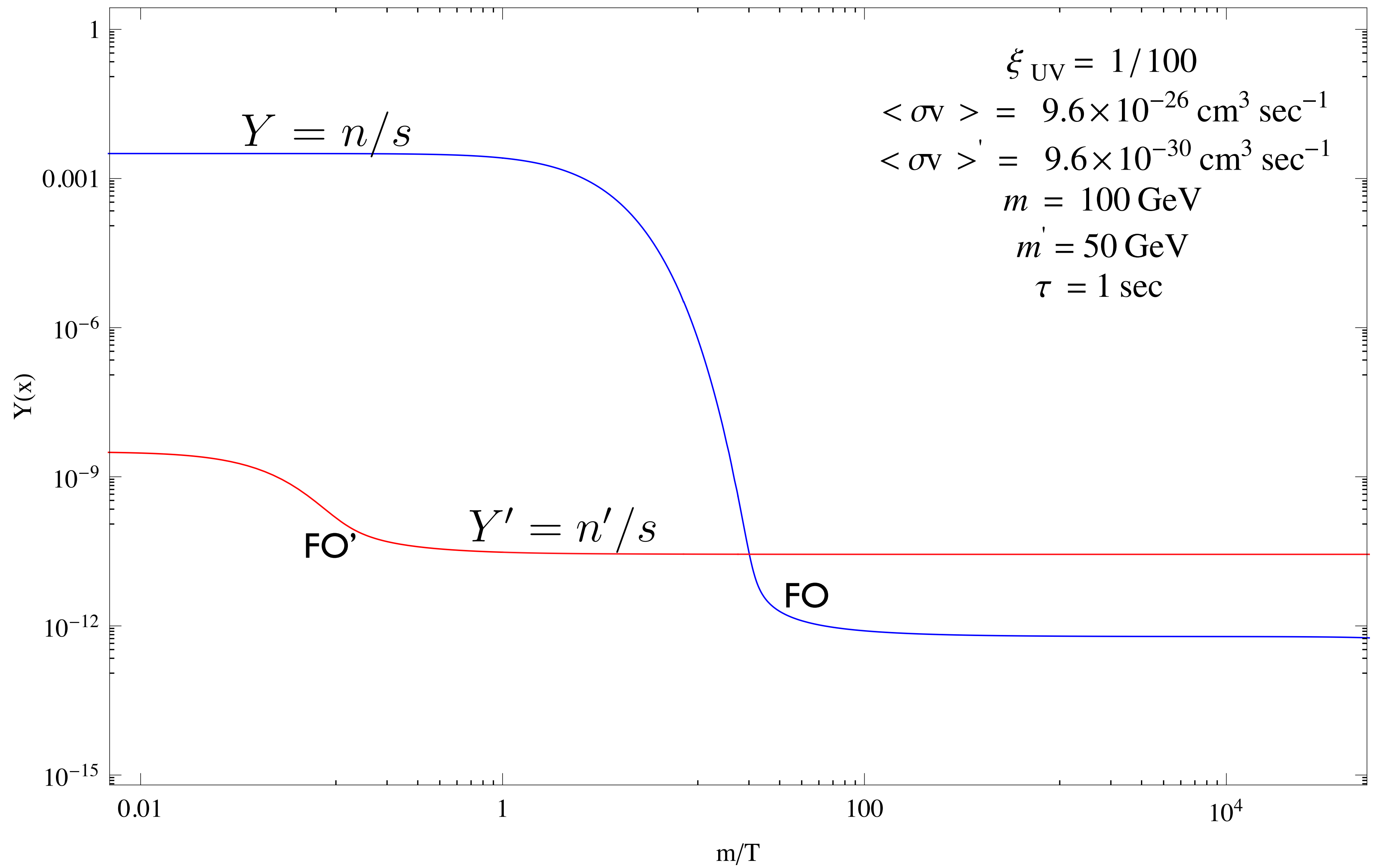
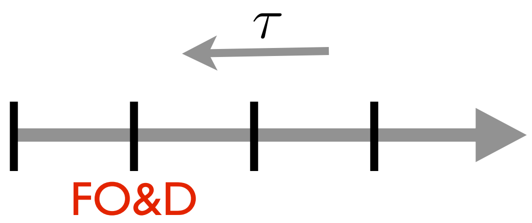


"Freeze out with hidden sector variables":

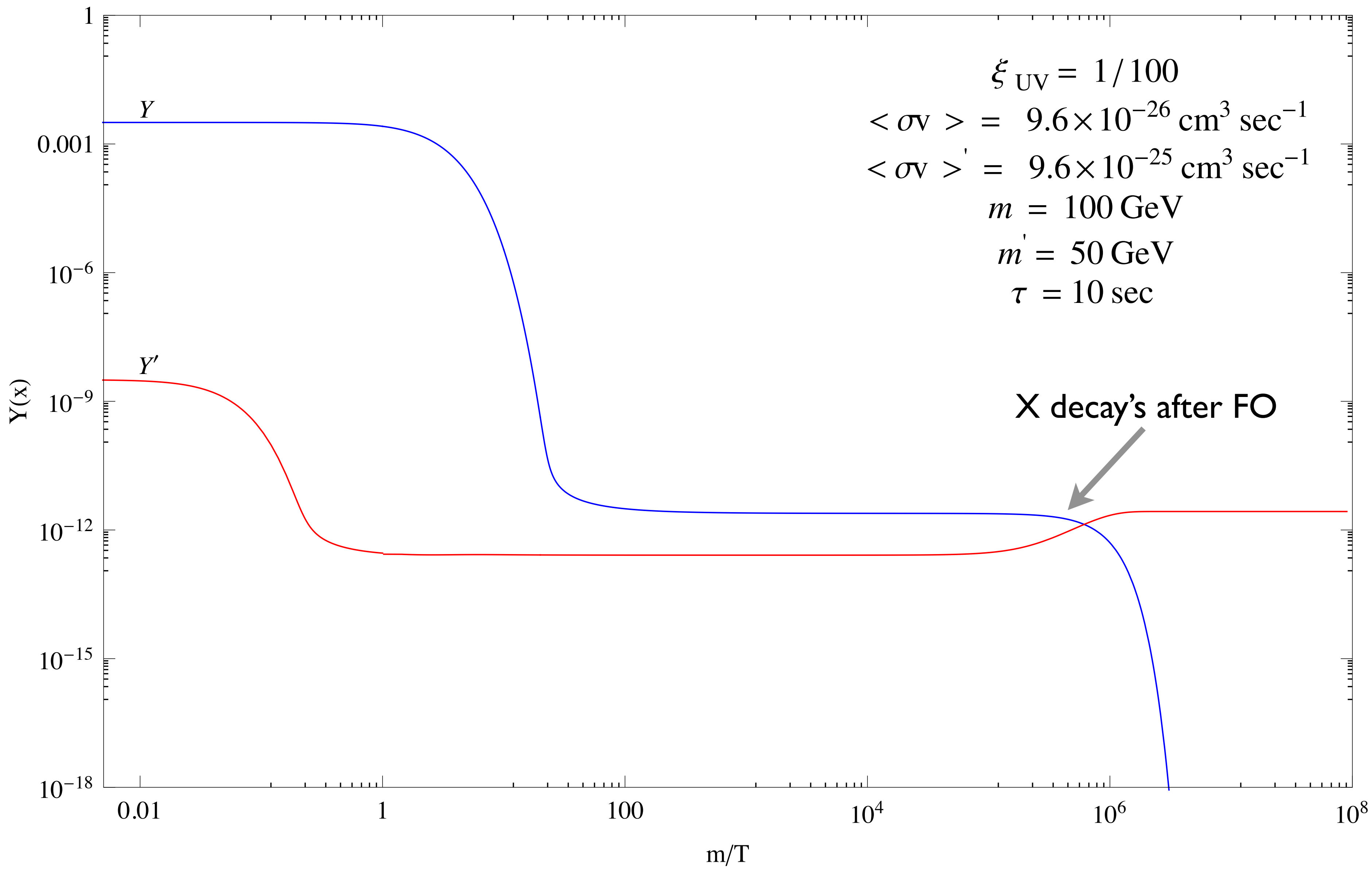
Not reconstructable

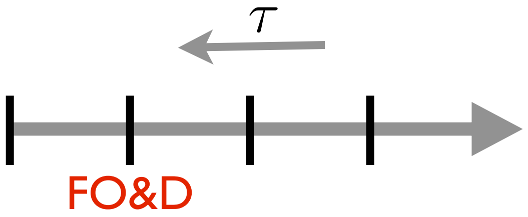
$$Y'_{\mathrm{FO}'} \propto \frac{\xi_{\mathrm{FO}'}}{m'\langle\sigma v\rangle'}$$



Freeze-Out and Decay

(Same mechanism but different setup from SuperWIMPs)





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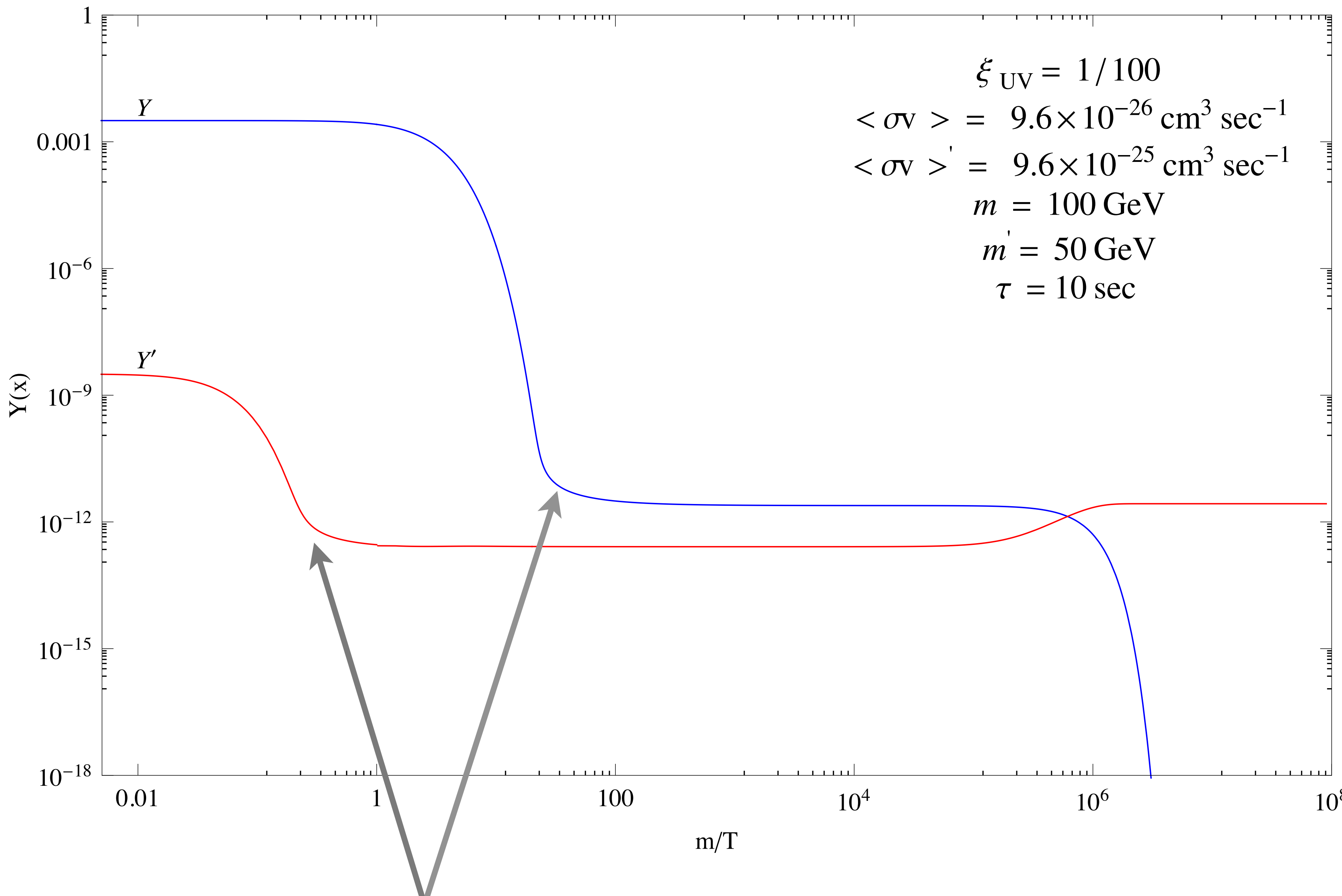
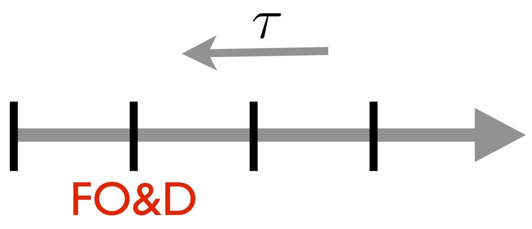


$\langle \sigma v \rangle << \langle \sigma v \rangle'$

FO' subdominant



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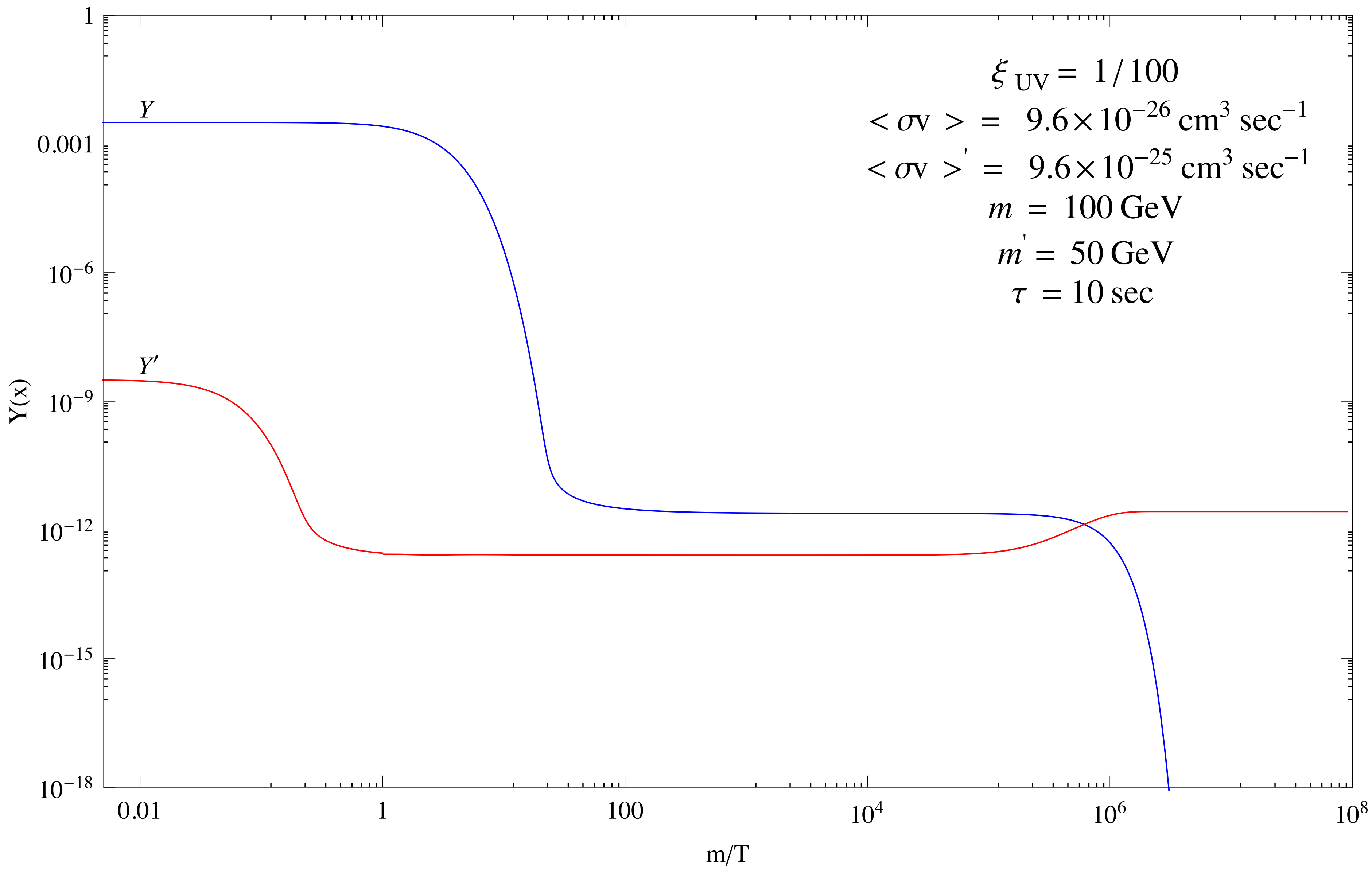
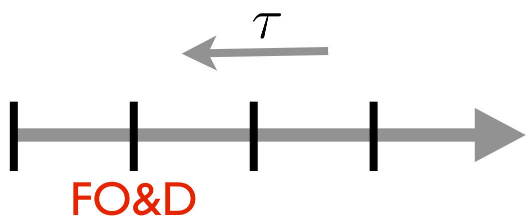


Every X decay yields exactly one X': $Y'_{\mathrm{FO\&D}} = Y_{\mathrm{FO}}$



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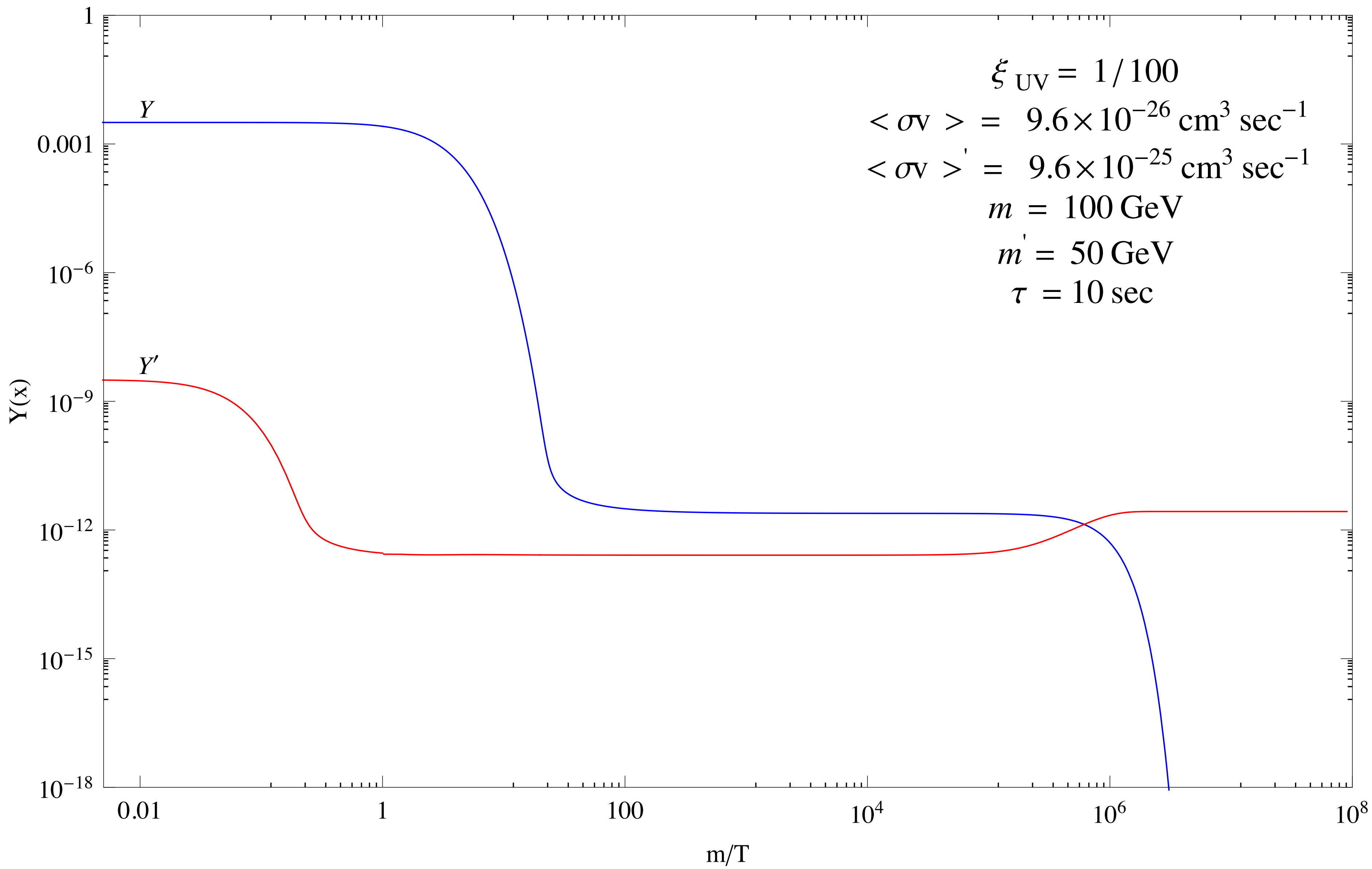
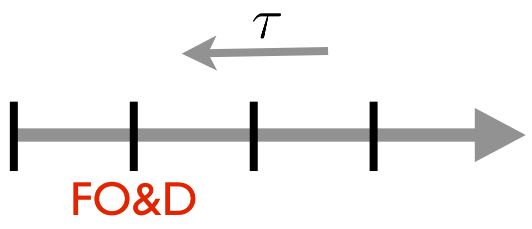


Every X decay yields exactly one X': $Y'_{\mathrm{FO\&D}} = Y_{\mathrm{FO}} \Rightarrow \Omega \propto \frac{m'}{m\langle\sigma v\rangle}$



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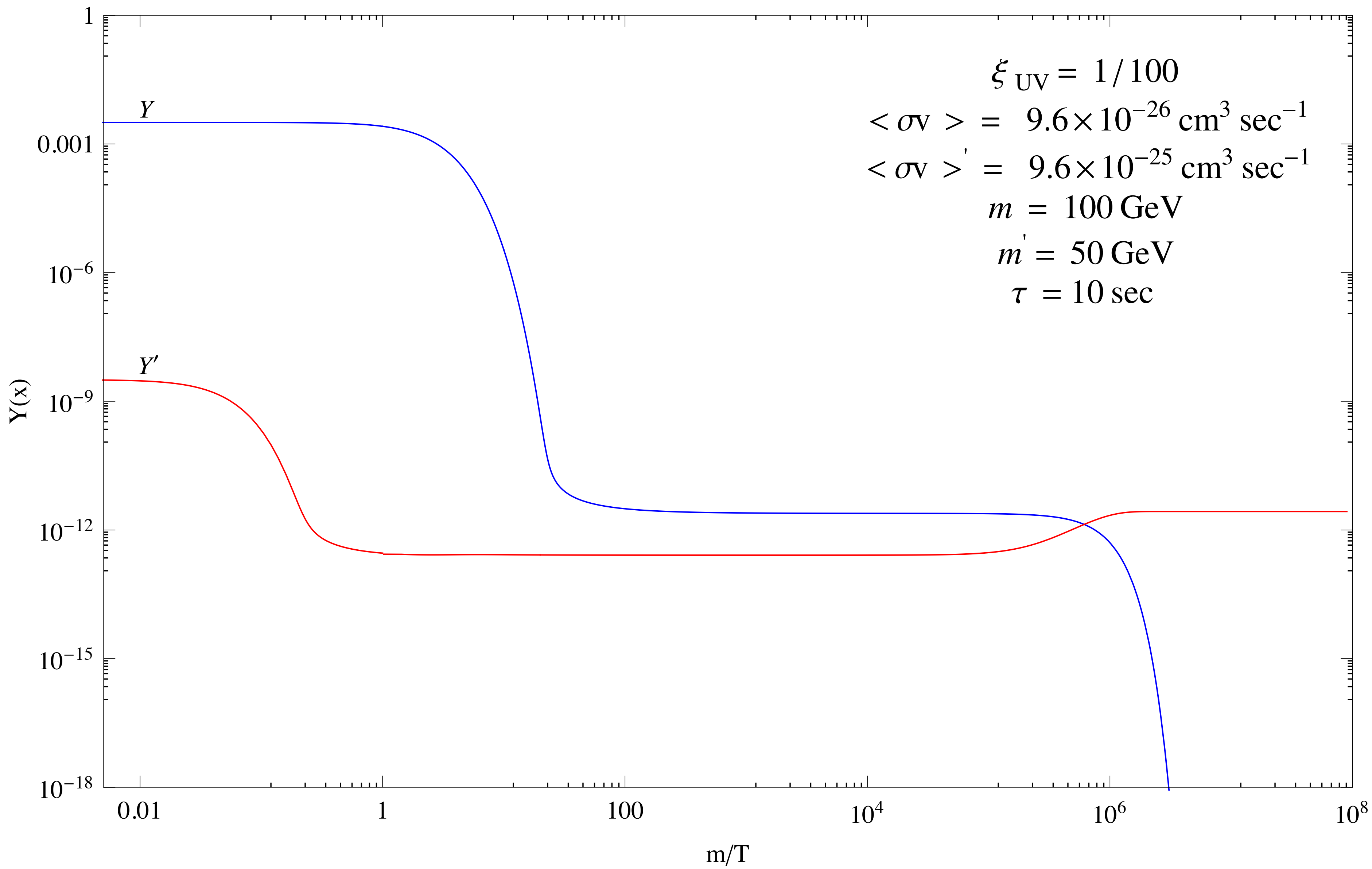

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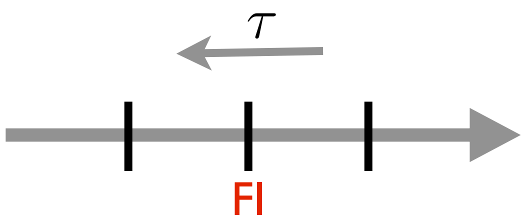
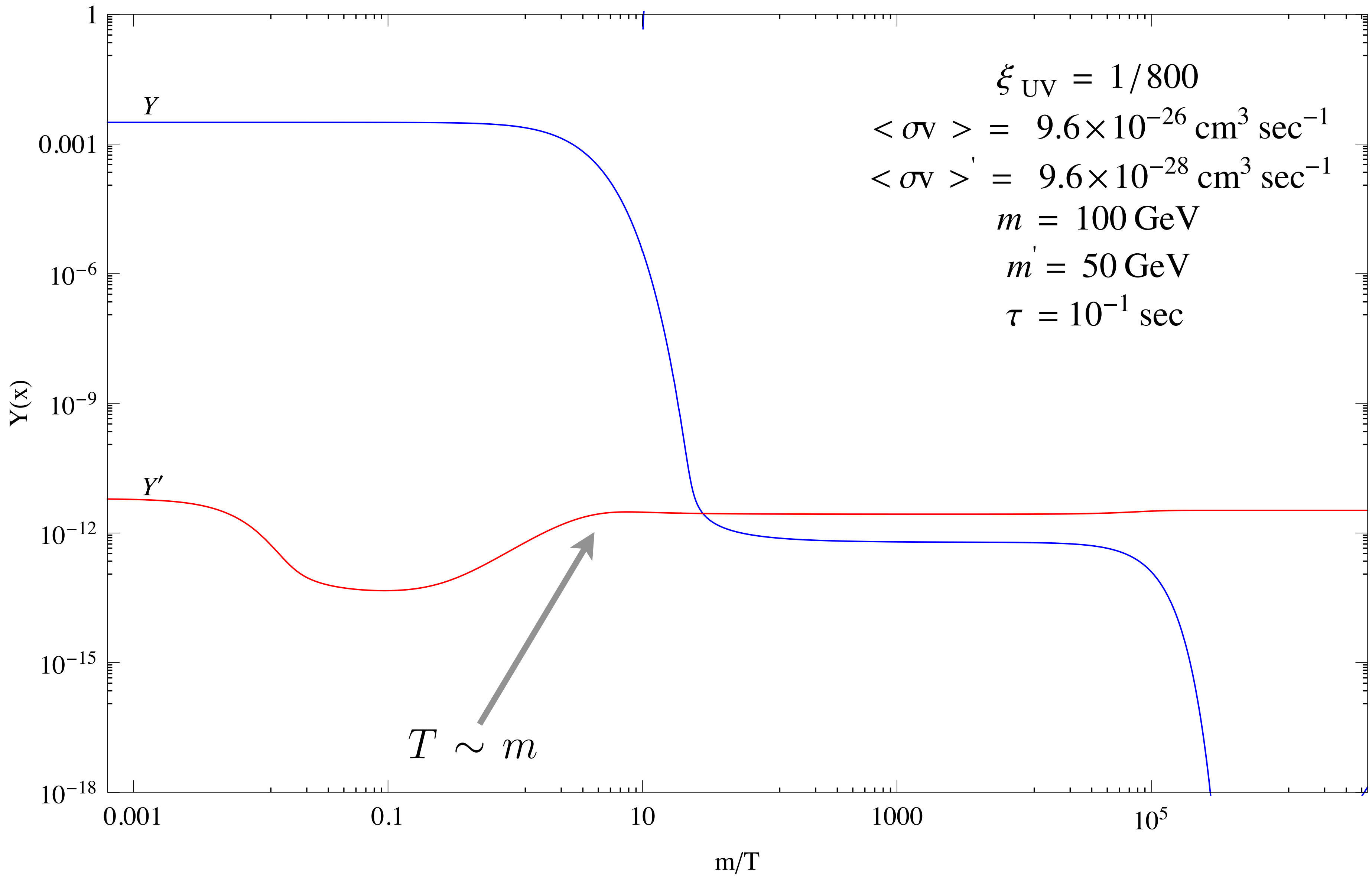
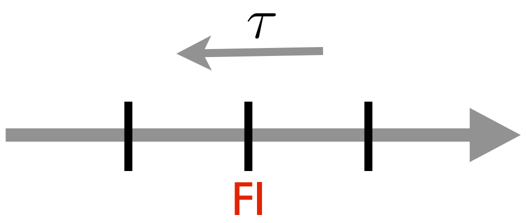
Reconstructable by measuring: $m, m', \langle\sigma v\rangle$

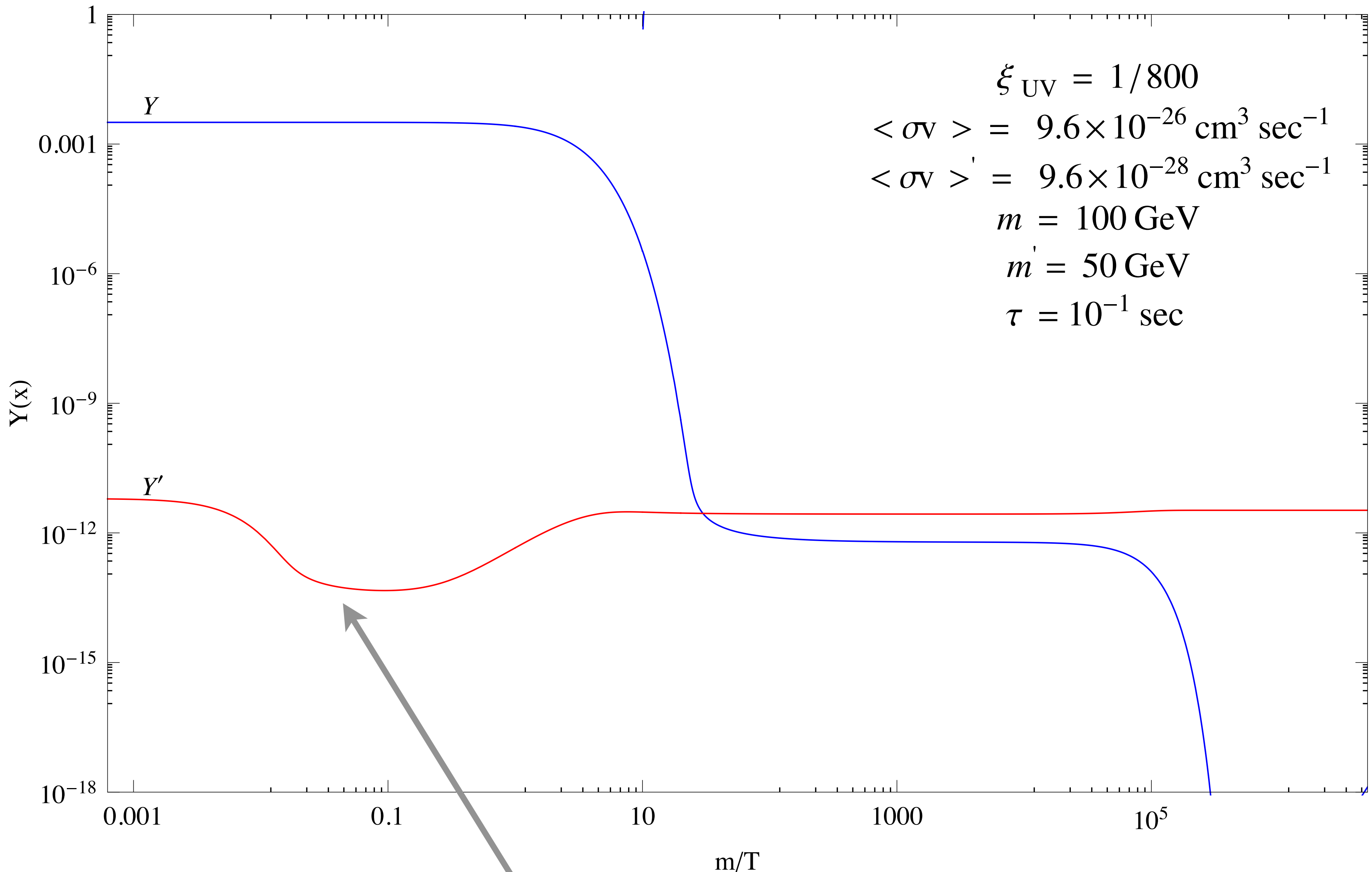

τ
FI

Freeze-In

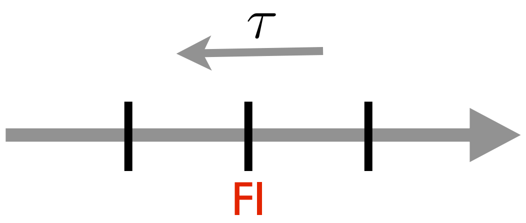

1
0.001
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
Y(x)
0.001
0.1
10
1000
10^5
m/T
Y
Y'
$\xi_{\mathrm{UV}} = 1/800$
$<\sigma v> = 9.6\times10^{-26}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}$
$<\sigma v>' = 9.6\times10^{-28}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}$
$m = 100\ \mathrm{GeV}$
$m' = 50\ \mathrm{GeV}$
$\tau = 10^{-1}\ \mathrm{sec}$
$T \sim m$



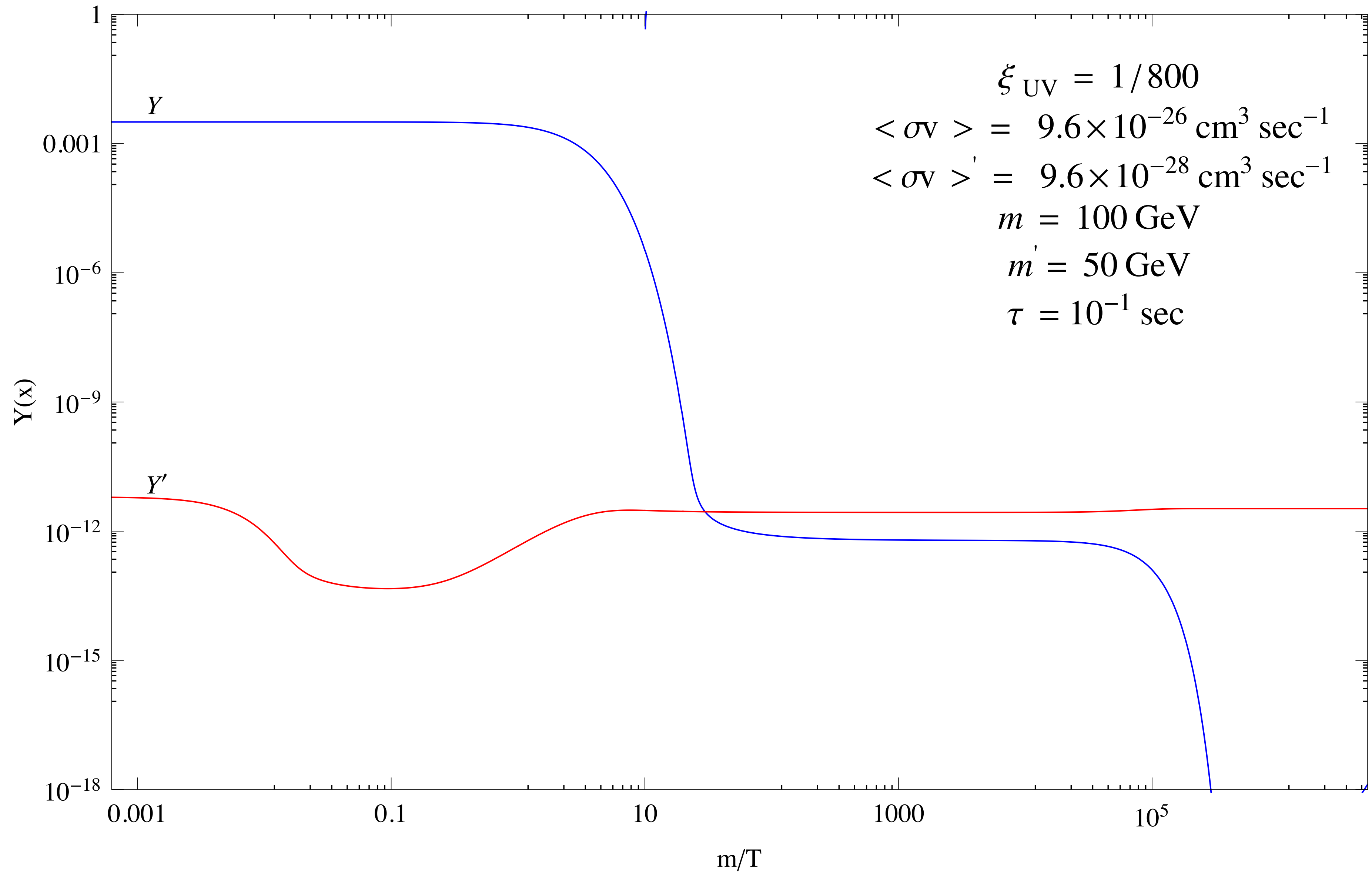
Freeze-In



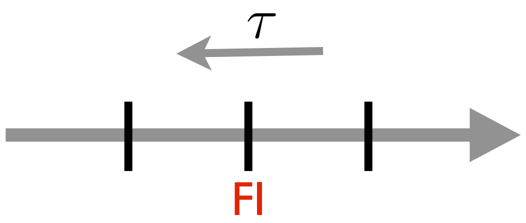
Note for FI to be effective it must occur after FO’



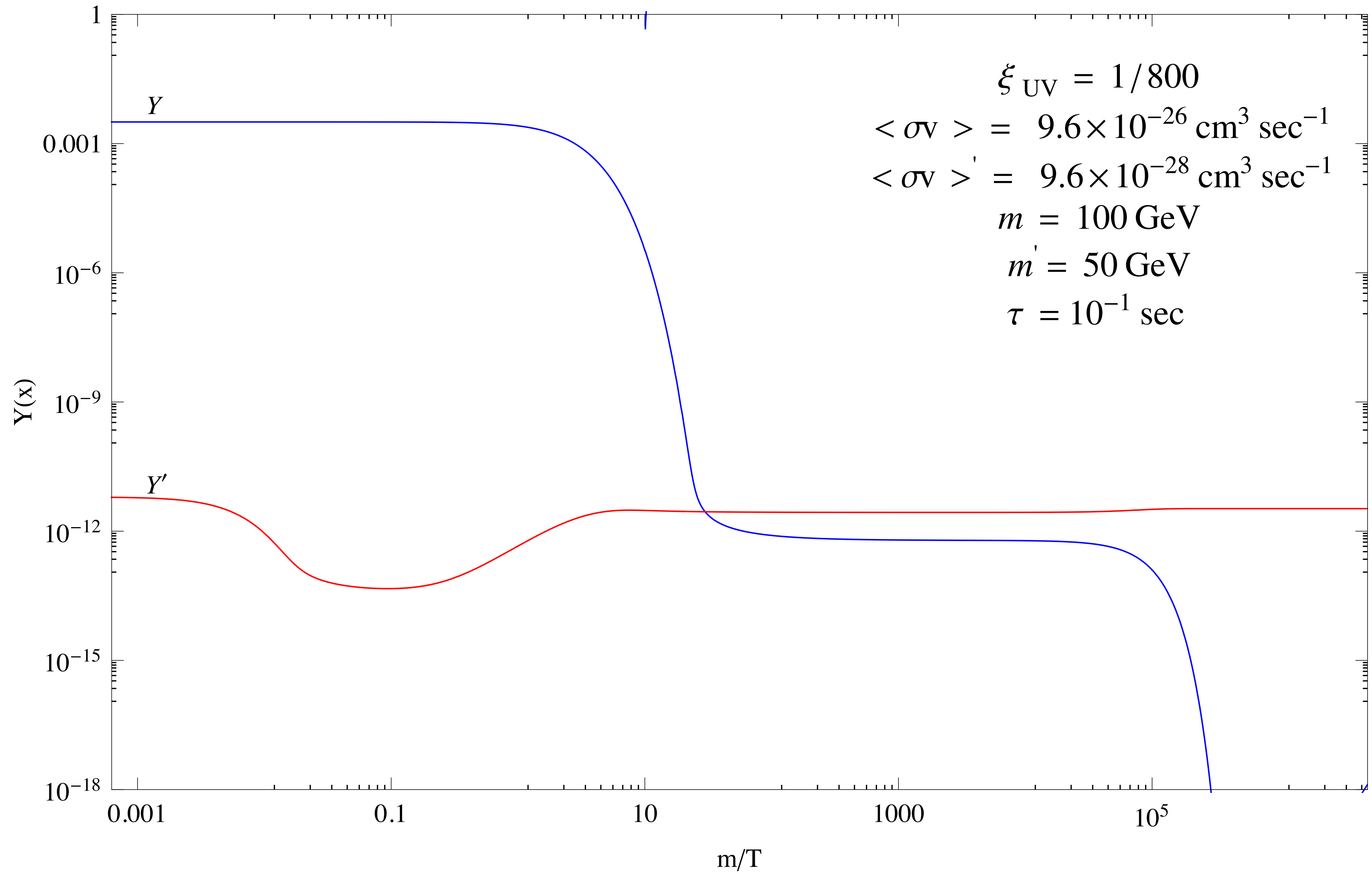
Freeze-In



Decay term dominates the Boltzmann equations: $Y'_{\rm FI} \propto \dfrac{1}{\tau m^2}$ $\quad \Omega \propto \dfrac{m'}{m^2 \tau}$



Freeze-In

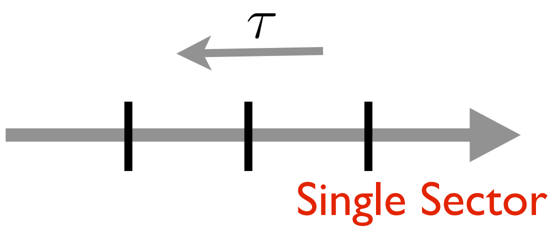


Decay term dominates the Boltzmann equations: $Y'_{\rm FI} \propto \dfrac{1}{\tau m^2} \Rightarrow \Omega \propto \dfrac{m'}{m^2\tau}$

$$\Omega_{DM}h^2 \sim 0.11 \Rightarrow \tau \simeq (4\times10^{-2}\ \mathrm{s})\left(\frac{m'}{m}\right)\left(\frac{100\mathrm{GeV}}{m}\right)\left(\frac{228.5}{g_\star}\right)^{3/2}$$

Reconstructable

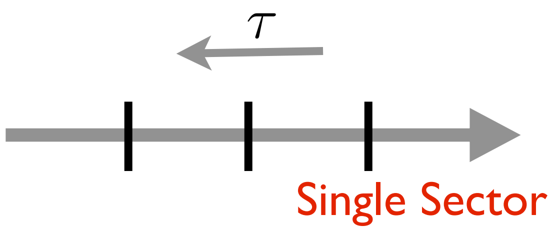
$L_{\rm FI} \sim 10^6$ meters   X decays could be seen in detectors.



Sector Equilibration

Connector operator couples the sectors so strongly that they come into thermal equilibrium.

$$\xi = T'/T \approx 1$$



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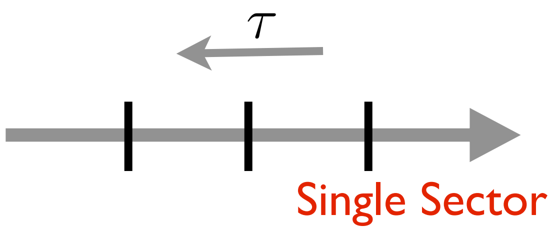
What is the minimum possible lifetime that corresponds to equilibration?



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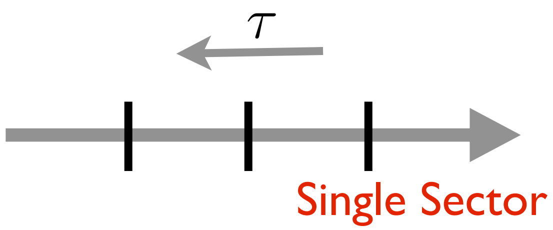

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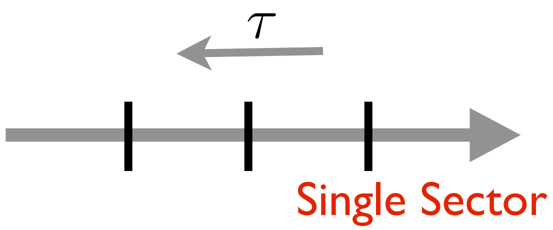
Since FI is exponentially switched off



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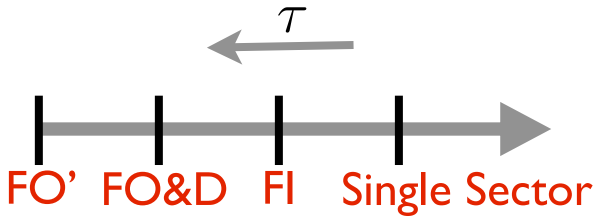
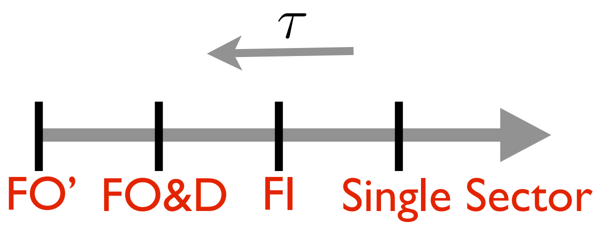
Freeze-In decays are strong enough to equilibrate the two sectors if:

$$\xi_{\rm IR}(T \simeq m) = 1$$

$$\Rightarrow \quad \tau_{\rm min} \simeq 10^{-13}\ {\rm s} \left(\frac{100\,{\rm GeV}}{m}\right)^2 \left(\frac{100}{g'_*(T \simeq m)/g_X}\right)$$



Complete?



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Could there be other effects due to the presence of multiple source terms in the Boltzmann equations?

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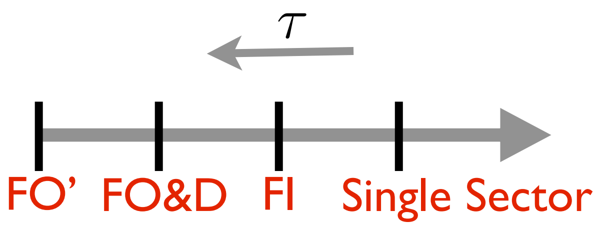

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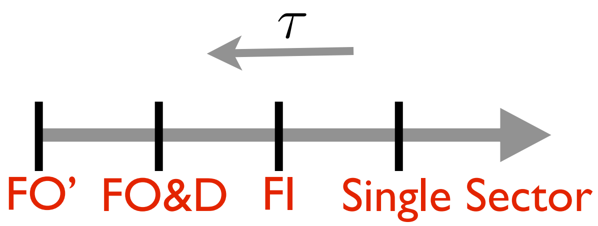
X' source term
driving FI or FO&D



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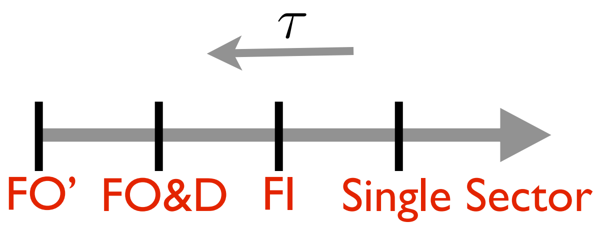

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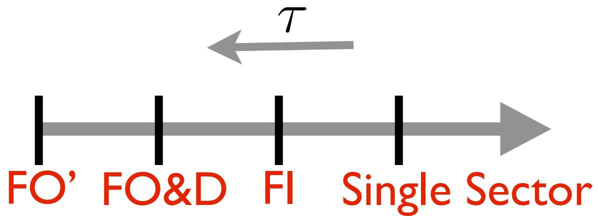

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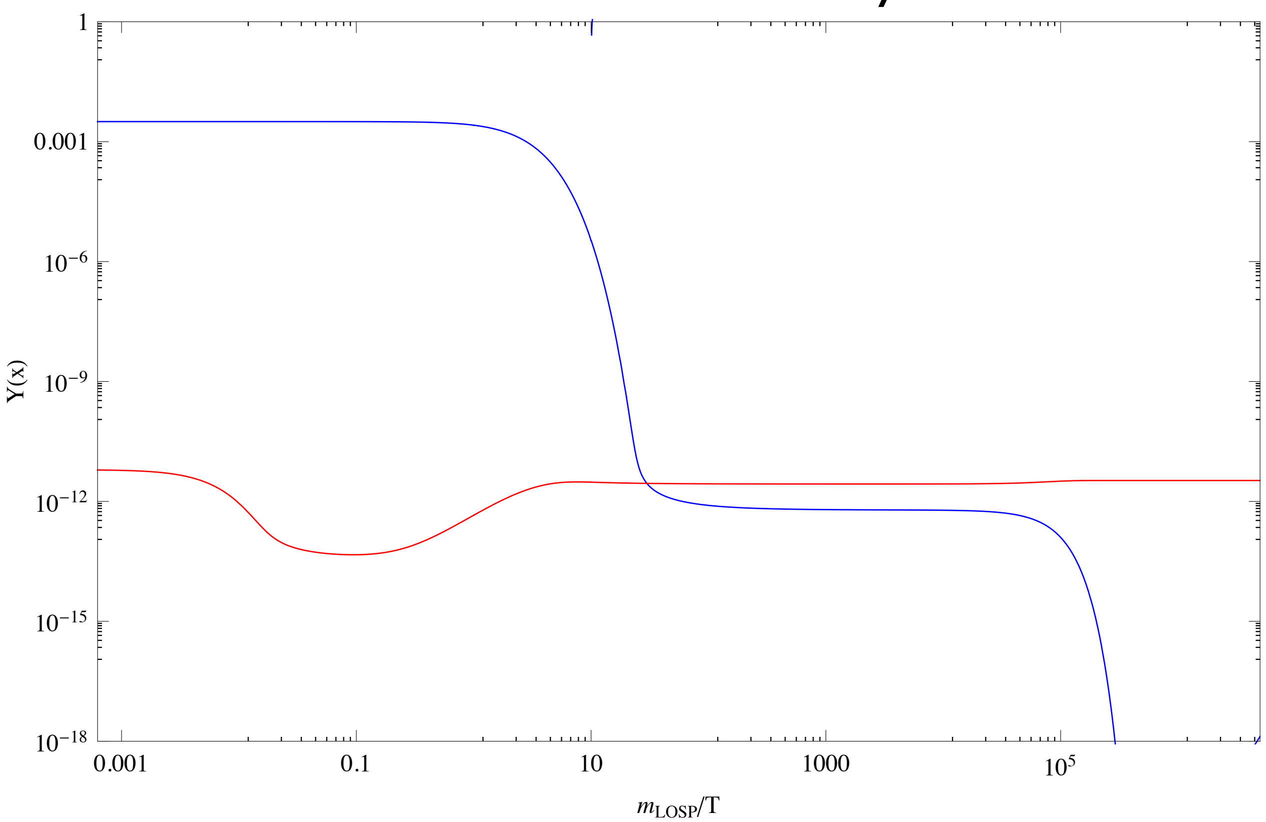
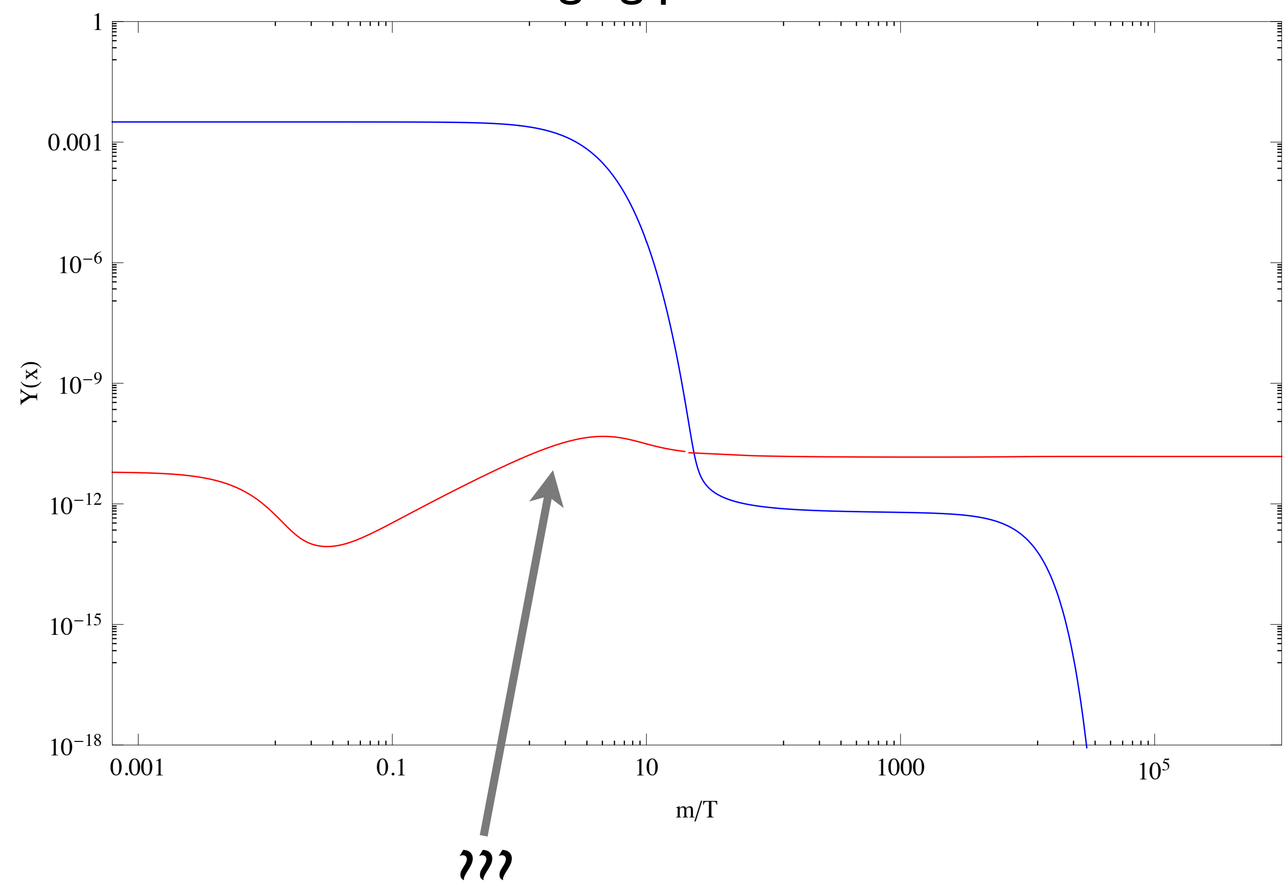
Final abundance dominated by Freeze-In



Changing parameters...



Re-Annihilations

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Multiple source terms can result in a modification of the FI and FO&D abundance

Recall X' is in thermal equilibrium as long as $Y' > \frac{H}{s\langle\sigma v\rangle'} = Y'_{crit}$

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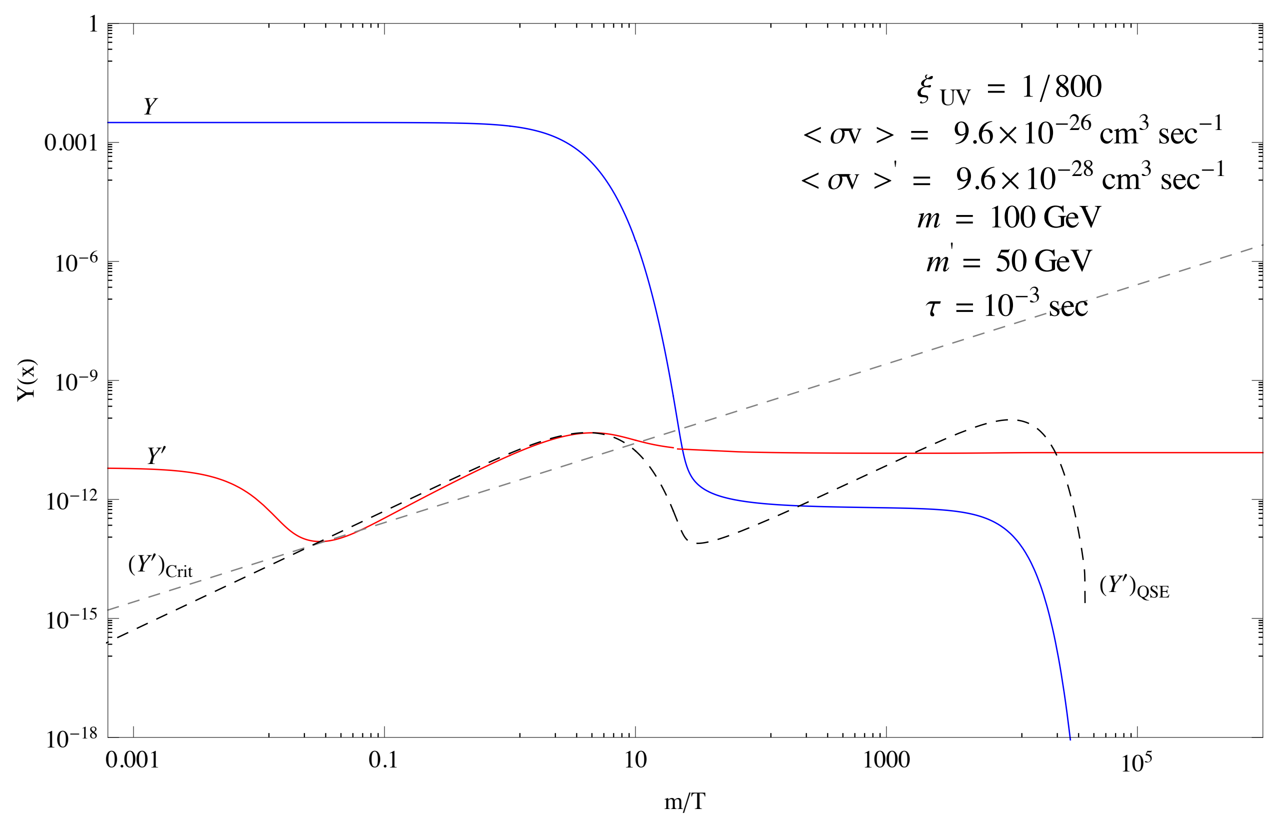

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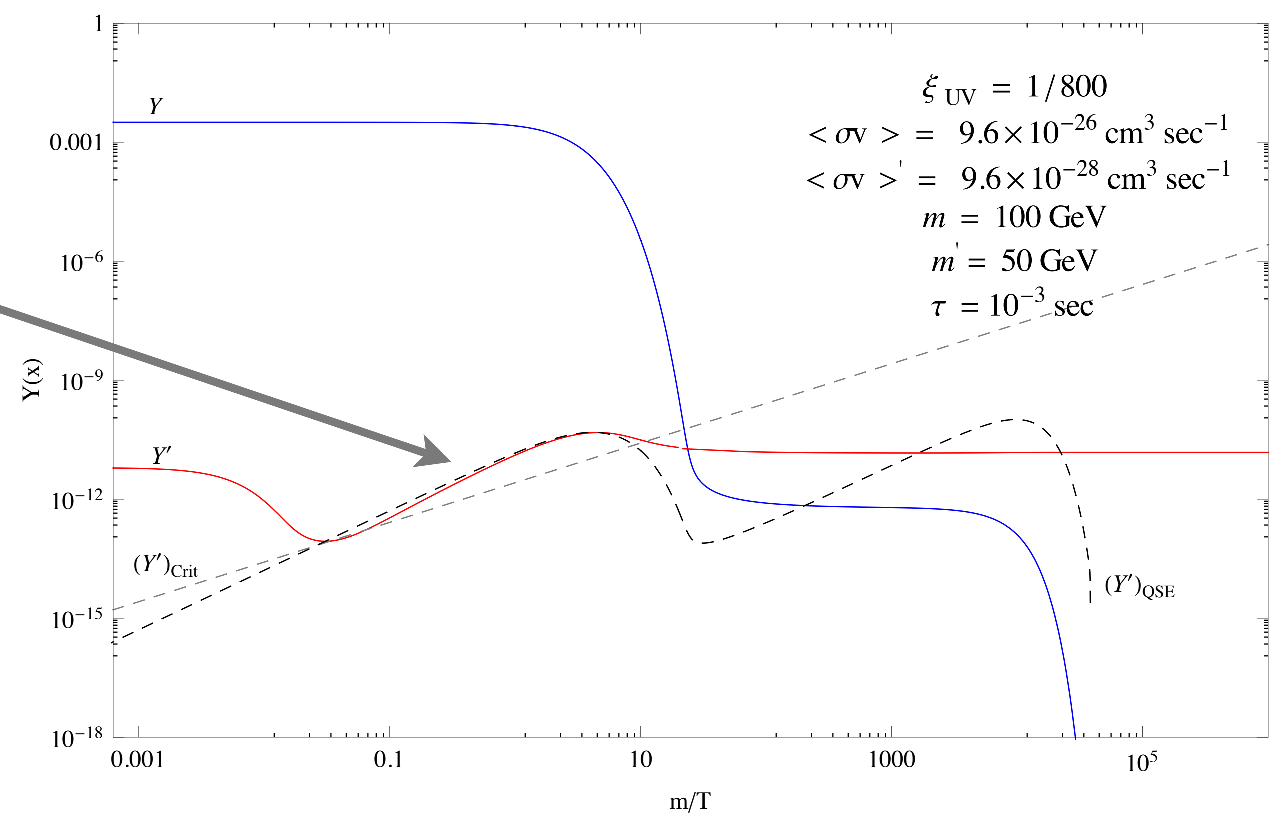
QSE will be maintained as long as $Y'_{\rm QSE} > Y'_{\rm crit}$



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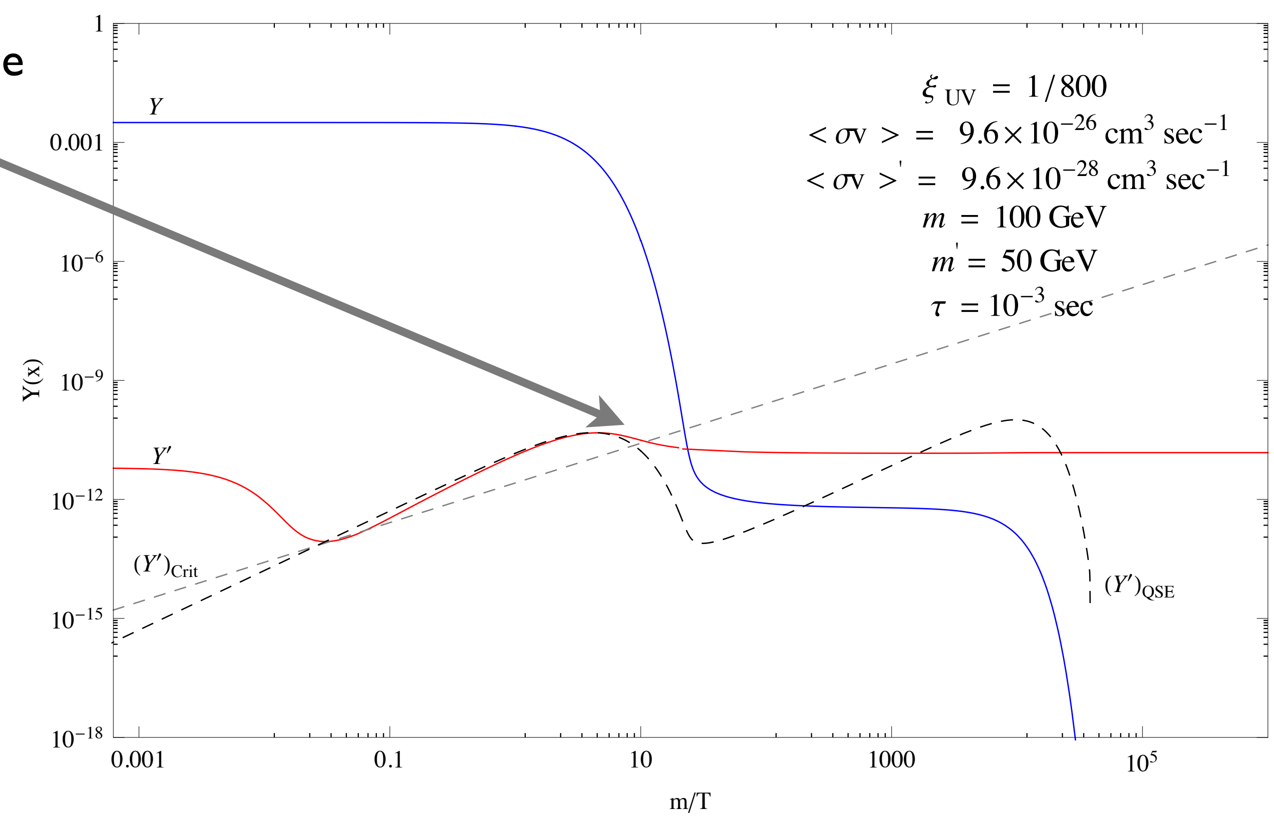
$$Y'_{\rm QSE}(T_{\rm r}) = Y'_{\rm crit}(T_{\rm r})$$



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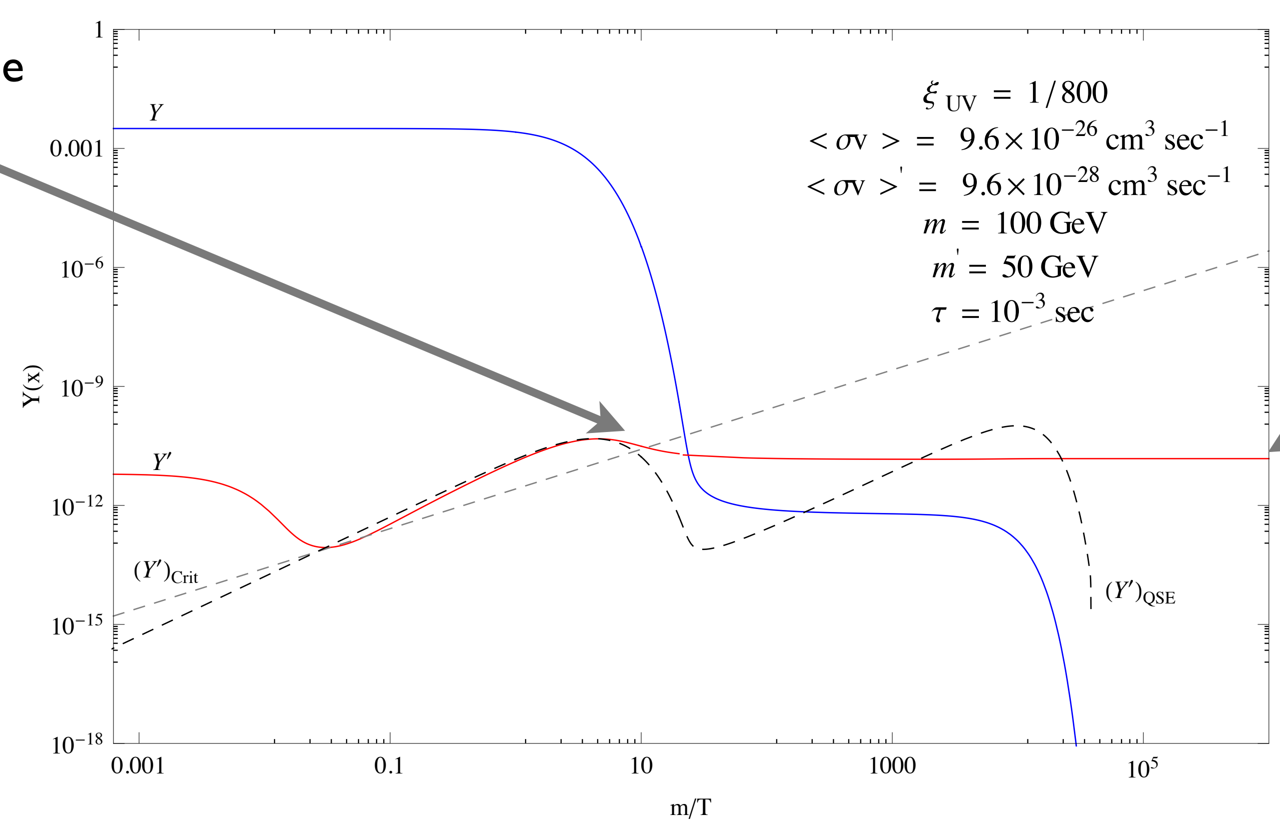

Resulting in a modified (smaller) FI yield which we call FI_r

$$Y'_{\rm FI_r} = Y'_{\rm crit}(T_{\rm FI_r})$$

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As sv increases Ycrit decreases and we stay in QSE longer so that the final yield is smaller.

$$Y'^2_{\rm QSE} = \frac{\Gamma Y}{H} Y'_{\rm crit} = \frac{\Gamma Y}{\langle\sigma v\rangle' s}$$

Ends when Y' falls below the critical yield at T_r

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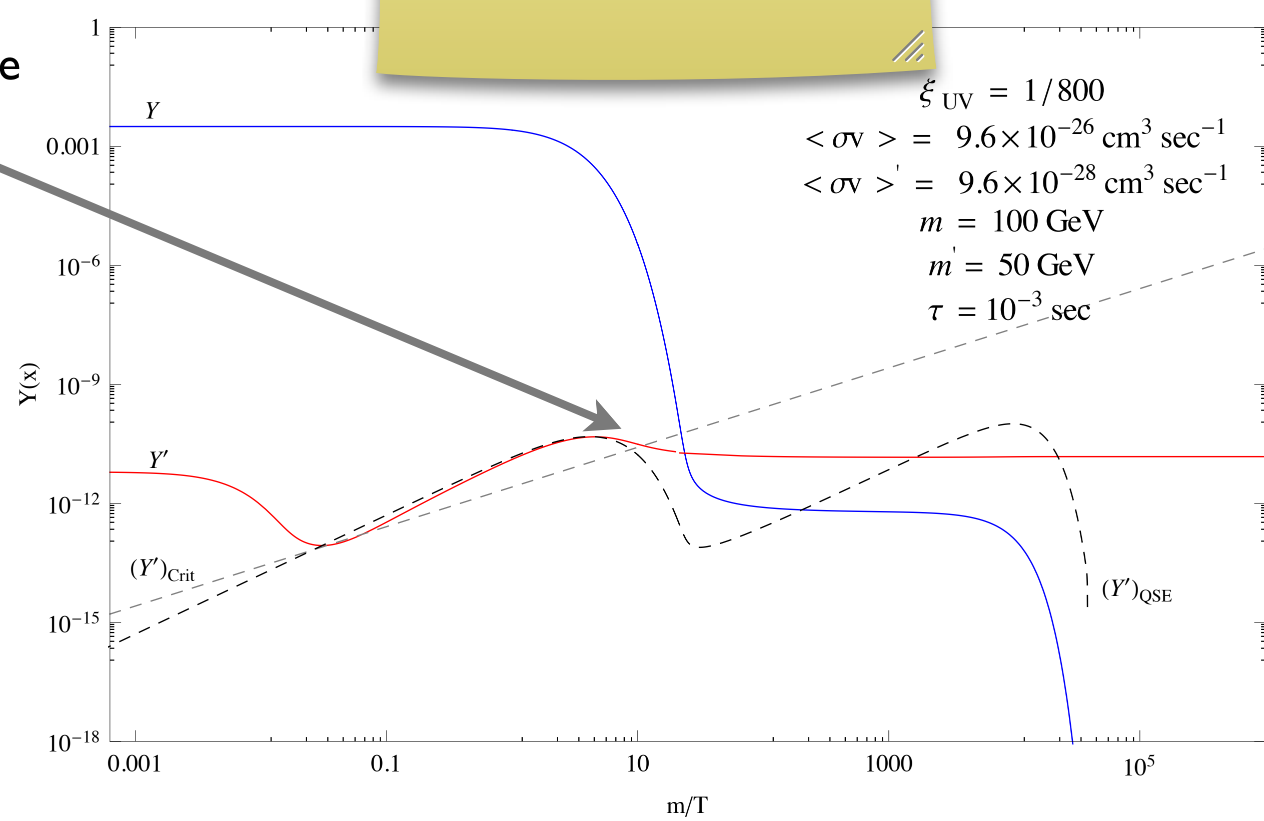

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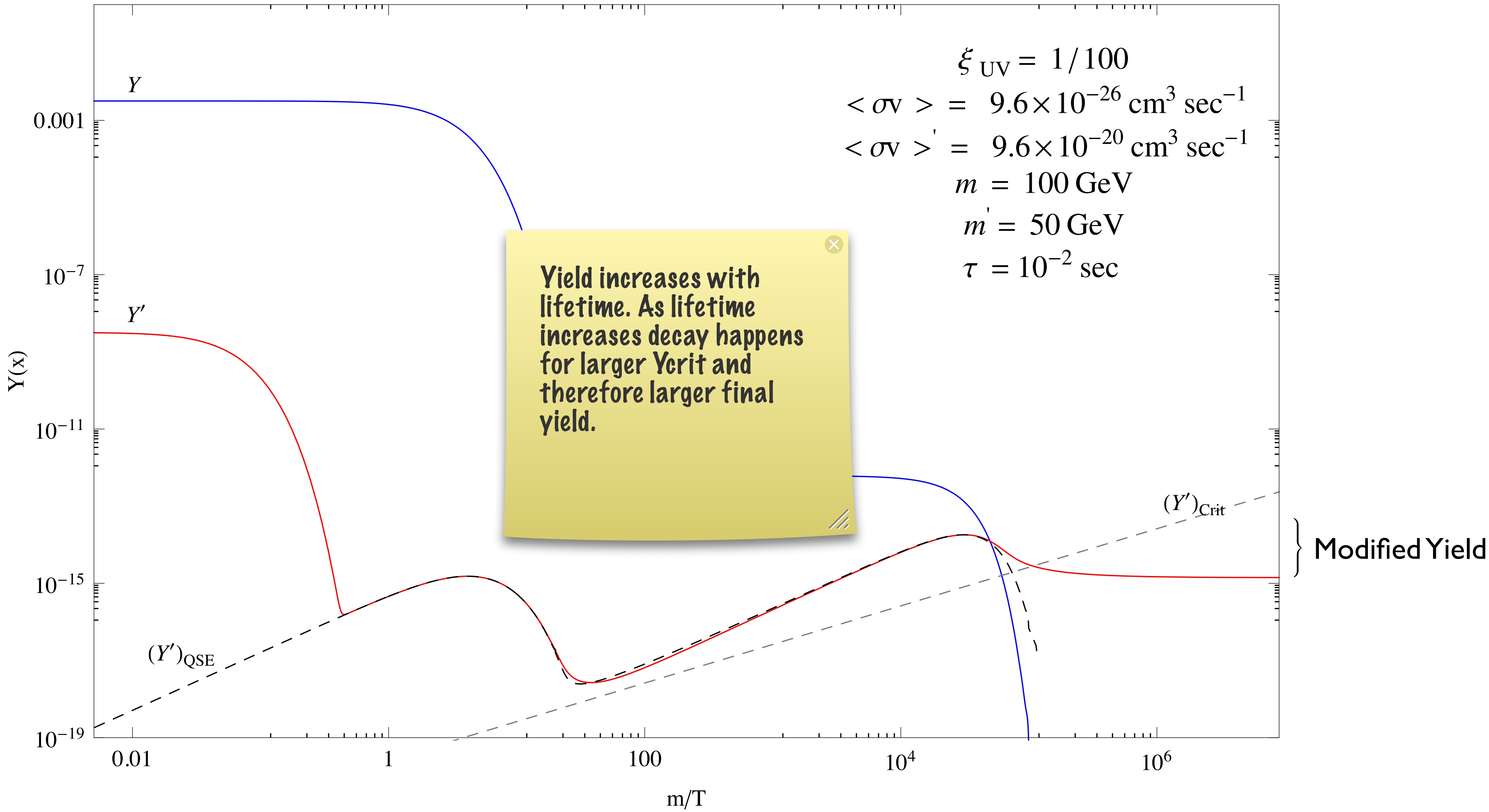
$$Y'_{\rm FI_r} = C_{\rm FO}\frac{1}{M_{\rm Pl}\langle\sigma v\rangle'}\frac{1}{T_{\rm FI_r}} \propto \frac{1}{m\langle\sigma v\rangle'}$$

Not Reconstructable

Freeze-Out and Decay with Re-Annihilation (FO&Dr)



$$Y'_{\mathrm{FO\&D_r}} = Y'_{\mathrm{crit}}(T_{\mathrm{FO\&D_r}}) \quad \Rightarrow \quad Y'_{\mathrm{FO\&D_r}} = C_{\mathrm{FO}} \frac{1}{M_{\mathrm{Pl}}\langle\sigma v\rangle'} \frac{1}{T_{\mathrm{FO\&D_r}}} \propto \frac{\sqrt{\tau}}{\langle\sigma v\rangle'}$$

Not Reconstructable

Summary

Portal coupling →

← X lifetime

Multi-Component: X is stable, sectors fully decoupled, X and X' comprise DM via FO and FO'

Freeze-In: X decays while it is still in thermal equilibrium

Freeze-Out and Decay: X Freezes out and late decays to X'

Single Sector: X decays so quickly that the visible and hidden sectors are thermalized at the weak scale.

FO&D and FI are in principle reconstructable as long as yield is not modified by re-annihilations.

$$\boxed{\begin{aligned}
Y'_{\mathrm{FO\&D}} &\propto \frac{1}{m\langle\sigma v\rangle} \\
Y'_{\mathrm{FI}} &\propto \frac{1}{\tau m^2} \\
Y'_{\mathrm{FO'}} &\propto \frac{\xi_{\mathrm{FO'}}}{m'\langle\sigma v\rangle'} \\
Y'_{\mathrm{FI_r}} &\propto \frac{1}{m\langle\sigma v\rangle'} \\
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Next: what does parameter space look like?

$$\{m, m', \langle\sigma v\rangle, \langle\sigma v\rangle', \xi, \tau, \epsilon\}$$

Cosmological Phase Diagrams

$$\langle\sigma v\rangle = \langle\sigma v\rangle_0 = 3\times 10^{-26}\ \mathrm{cm^3/s}$$
$$m = 100\,\mathrm{GeV},\ m' = 50\,\mathrm{GeV}$$
$$\xi_{\mathrm{UV}} = 0.01$$

$$Y'_{\mathrm{FO\&D}} \propto \frac{1}{m\langle\sigma v\rangle}$$

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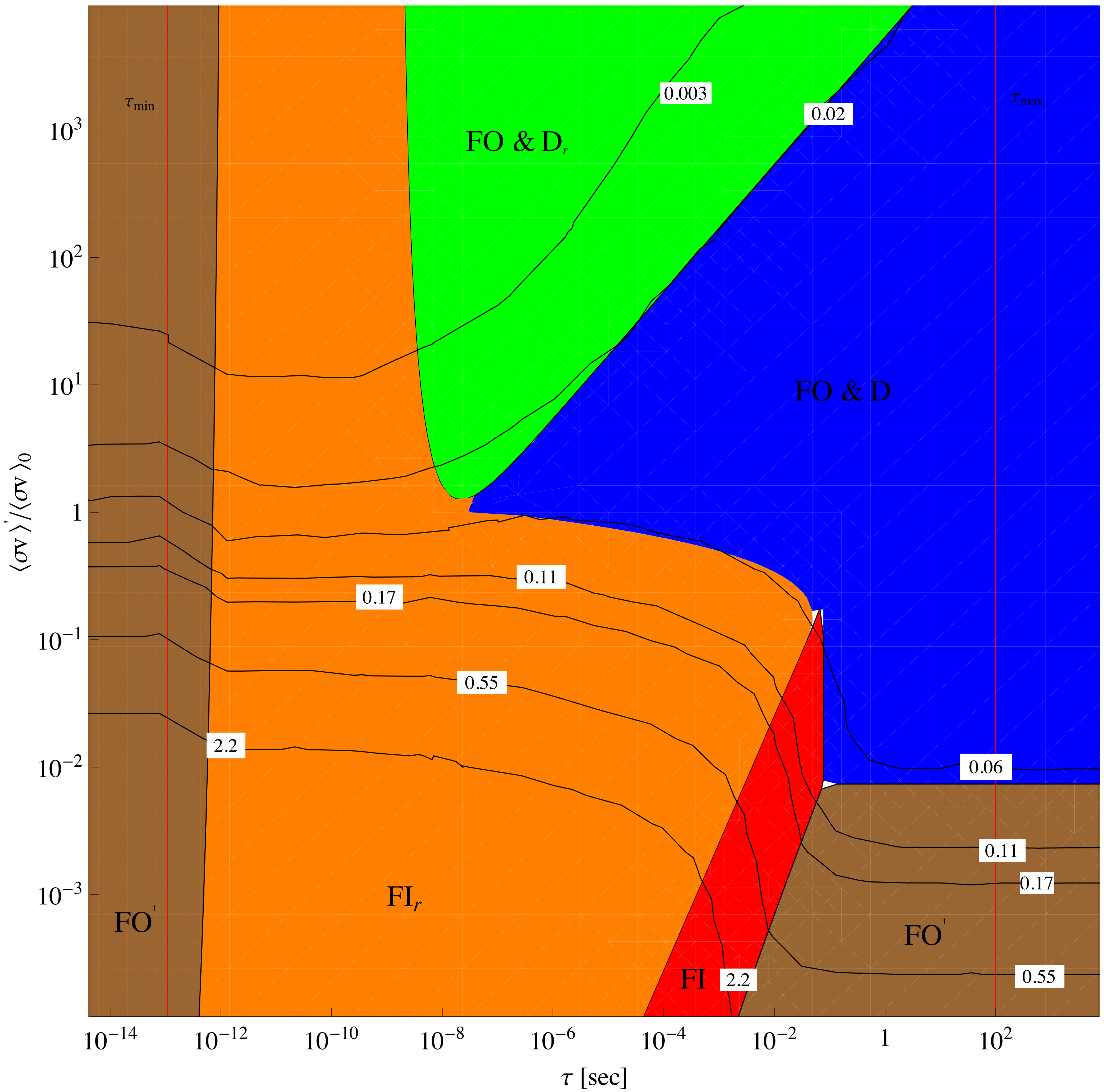
$$\xi^4_{FO'}(\tau) \sim \xi^4_{UV} + \frac{\#}{\tau^2}$$



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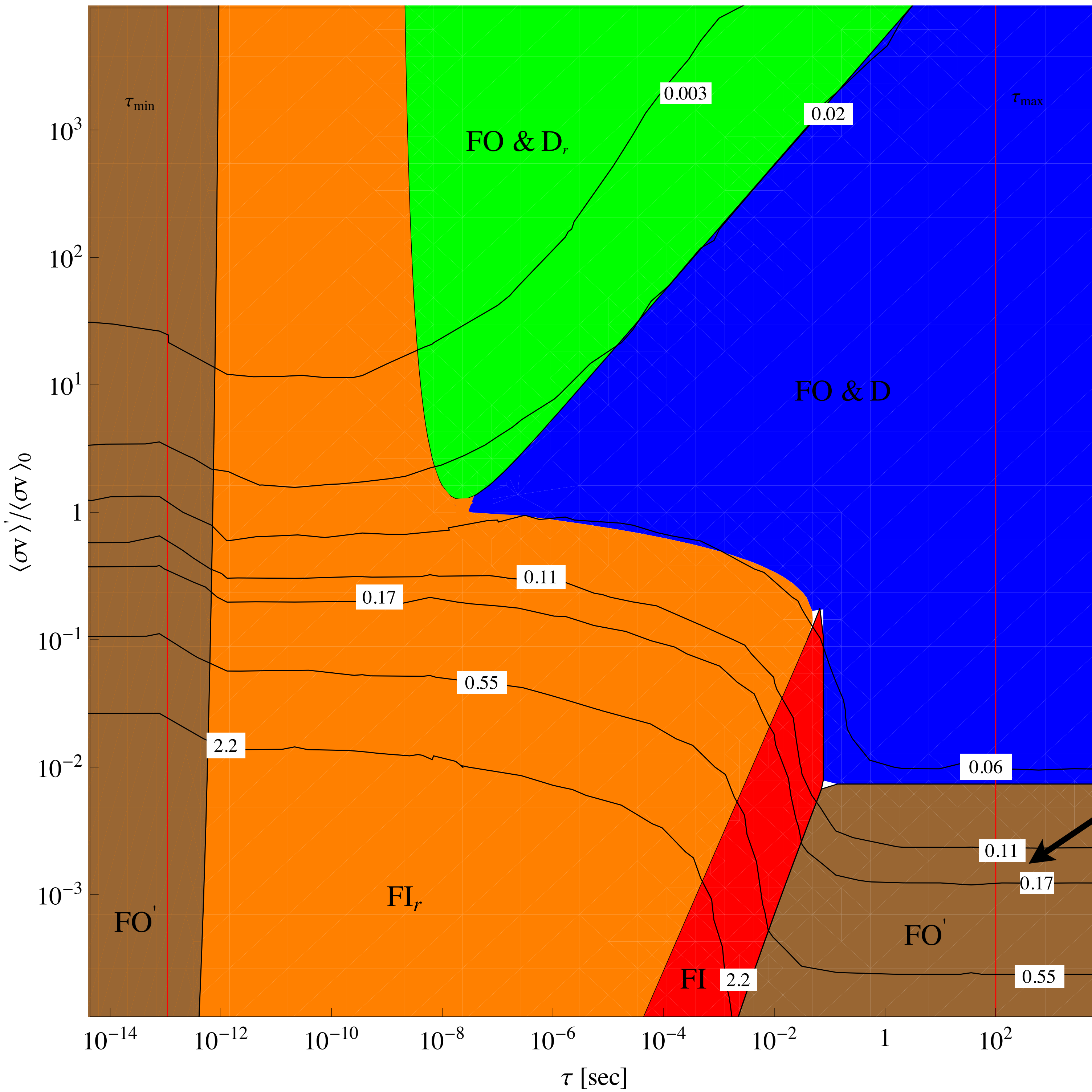

Numerical contour of fixed relic abundance.

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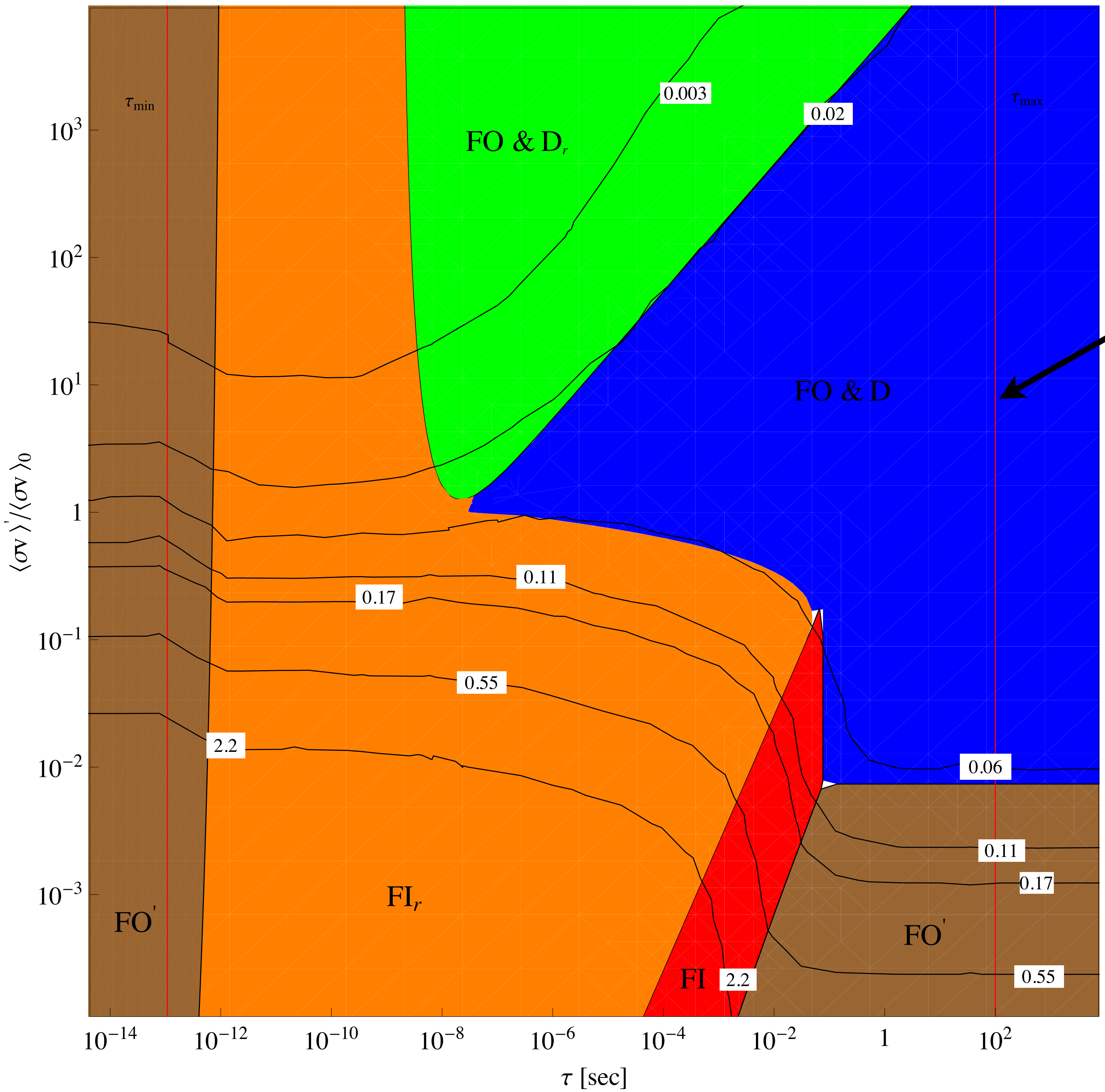

BBN bound

[M. Kawasaki, K. Kohri, T. Moroi, A. Yotsuyanagi arXiv:0804.3745]

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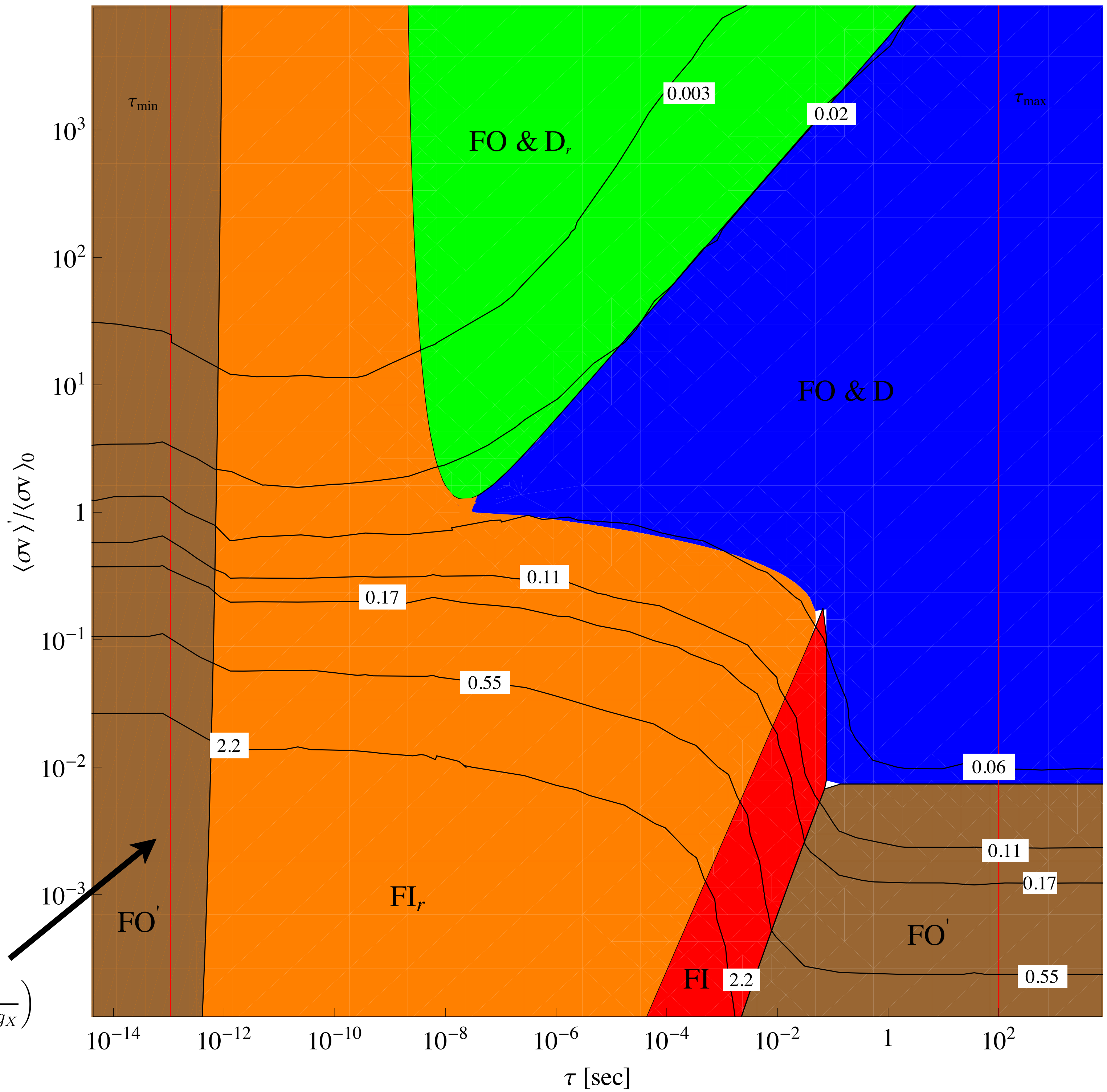

Thermalization bound

$$\tau_{\mathrm{min}} \simeq 10^{-13}\ \mathrm{s}\left(\frac{100\ \mathrm{GeV}}{m}\right)^2\left(\frac{100}{g'_*(T\simeq m)/g_X}\right)$$

Cosmological Phase Diagra

$\langle \sigma v \rangle$

m

$$Y'_{\mathrm{FO\&D}} \propto \frac{1}{m\langle \sigma v \rangle}$$

$$Y'_{\mathrm{FI}} \propto \frac{1}{\tau m^2}$$

$$Y'_{\mathrm{FO}'} \propto \frac{\xi_{\mathrm{FO}'}}{m'\langle \sigma v \rangle'}$$

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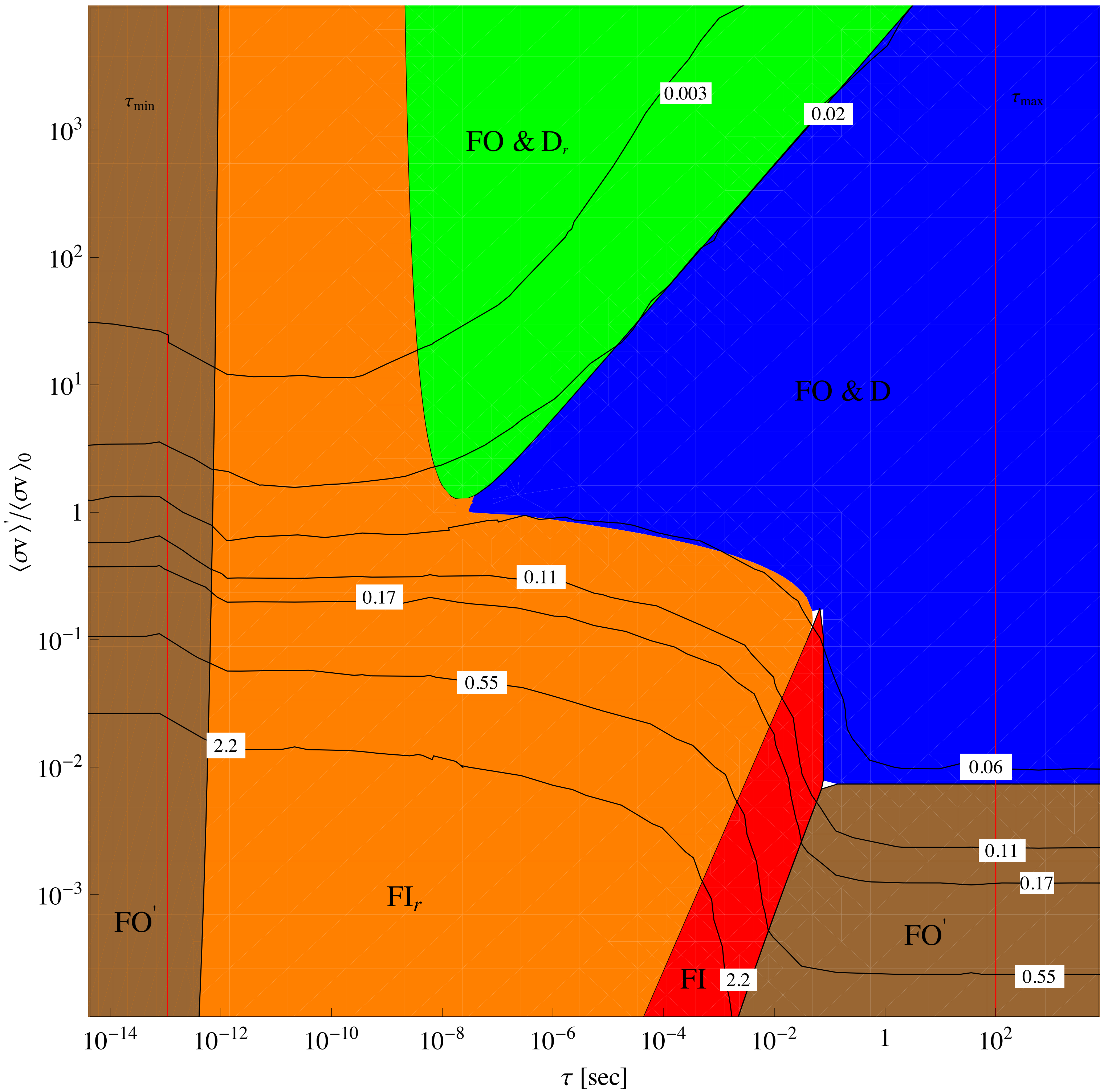

Talk about contours and regions.

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$$Y'_{\mathrm{FO\&D}} \propto \frac{1}{m\langle\sigma v\rangle}$$

$$Y'_{\mathrm{FI}} \propto \frac{1}{\tau m^2}$$

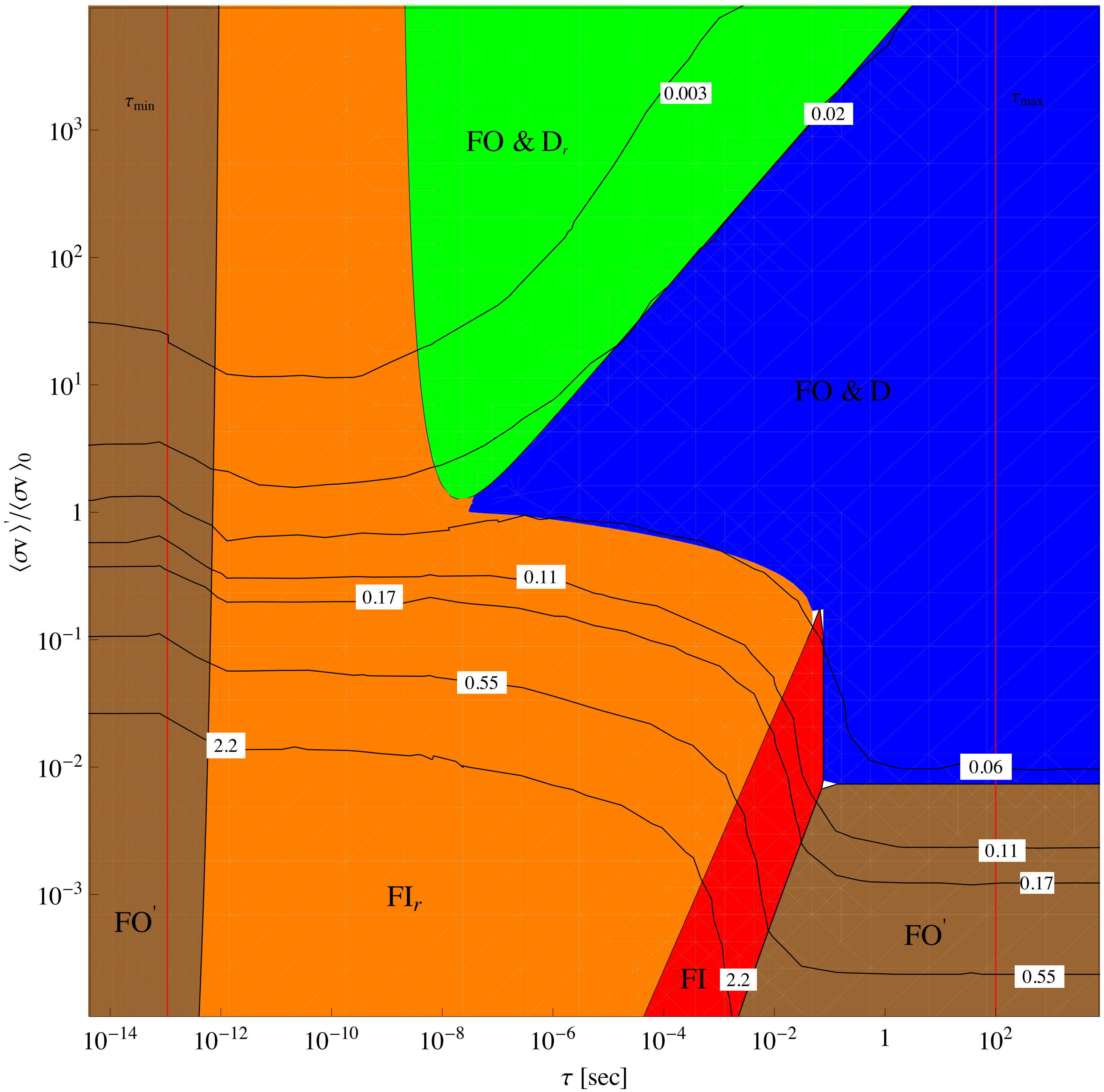
$$Y'_{\mathrm{FO'}} \propto \frac{\xi_{\mathrm{FO'}}}{m'\langle\sigma v\rangle'}$$

$$Y'_{\mathrm{FI_r}} \propto \frac{1}{m\langle\sigma v\rangle'}$$

$$Y'_{\mathrm{FO\&D_r}} \propto \frac{\sqrt{\tau}}{\langle\sigma v\rangle'}$$

$$\xi^4_{FO'}(\tau) \sim \xi^4_{UV} + \frac{\#}{\tau^2}$$

$$\langle\sigma v\rangle = \langle\sigma v\rangle_0 = 3 \times 10^{-26}\ \mathrm{cm^3/s}$$
$$m = 100\,\mathrm{GeV},\ m' = 50\,\mathrm{GeV}$$
$$\xi_{\mathrm{UV}} = 0.01$$

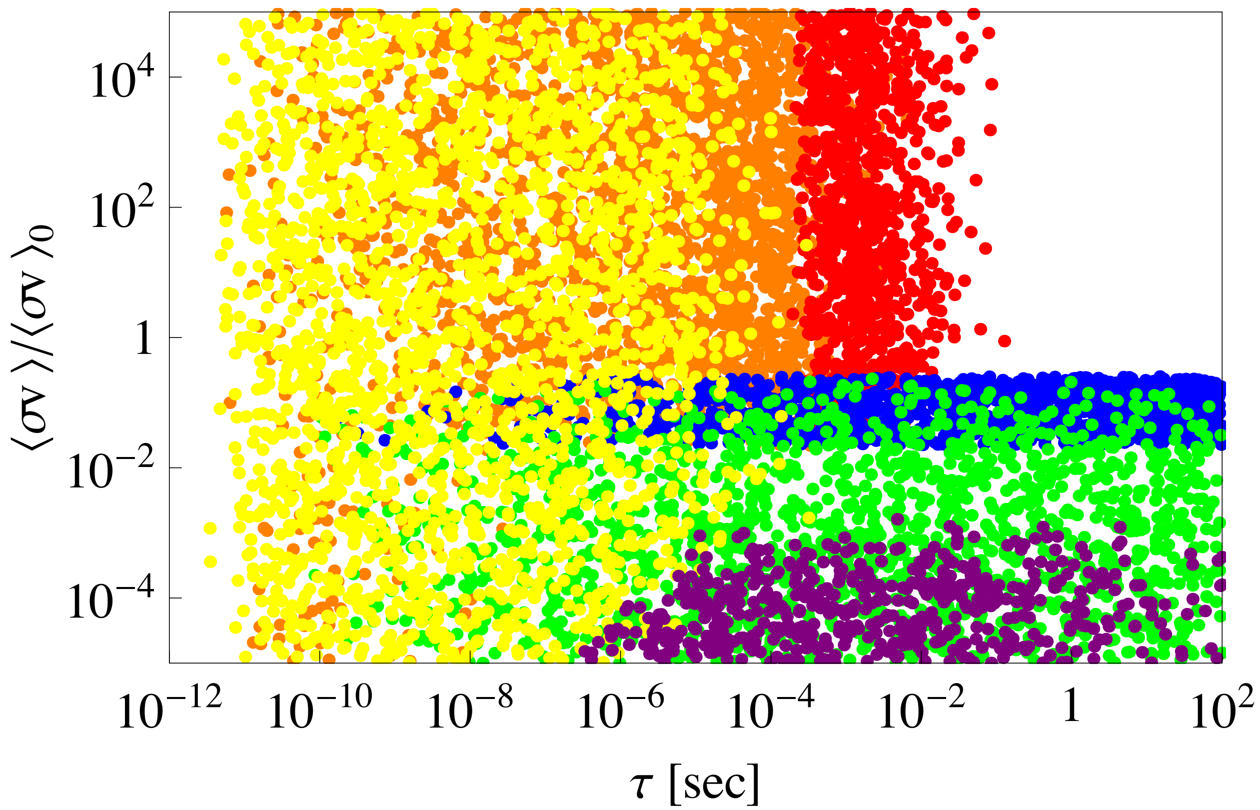


Still need to enforce Dark Matter constraint...

Getting the Right Relic Abundance

$$\Omega_{DM} h^2 \sim 0.11$$

Production mechanisms map to distinct window in parameter space:



$10 \text{ GeV} < m < 1 \text{ TeV}$

$1/20 < m'/m < 1/2$

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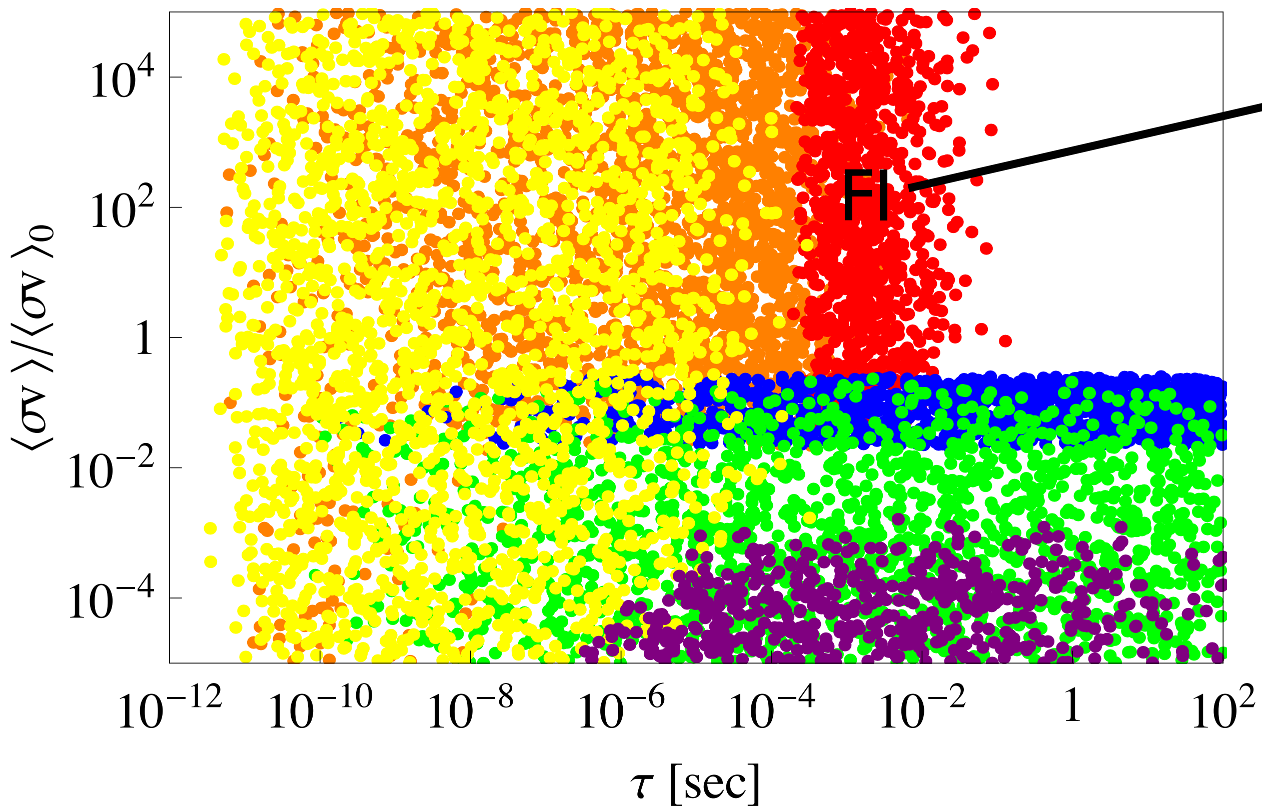

$$10 \text{ GeV} < m < 1 \text{ TeV}$$
$$1/20 < m'/m < 1/2$$

$$\tau \simeq \left(4 \times 10^{-2} \text{ s}\right) \left(\frac{m'}{m}\right) \left(\frac{100\text{GeV}}{m}\right) \left(\frac{228.5}{g_\star}\right)^{3/2}$$

$$L_{\mathrm{FI}} \sim 10^6 \text{ meters} \times \gamma \left(\frac{m'/m}{0.25}\right) \left(\frac{300\text{GeV}}{m}\right)$$

Decays could be seen in detectors.

Getting the Right Relic Abundance

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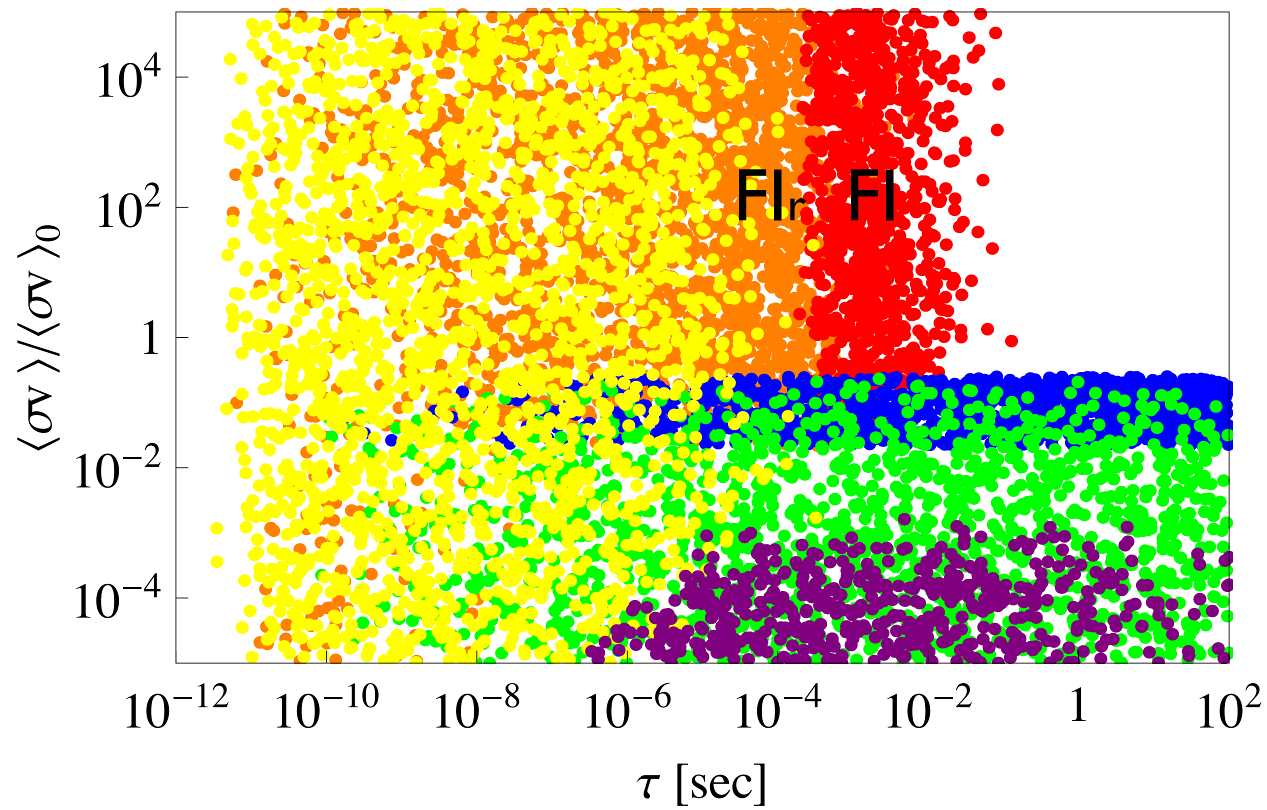
Production mechanisms map to distinct window in parameter space:



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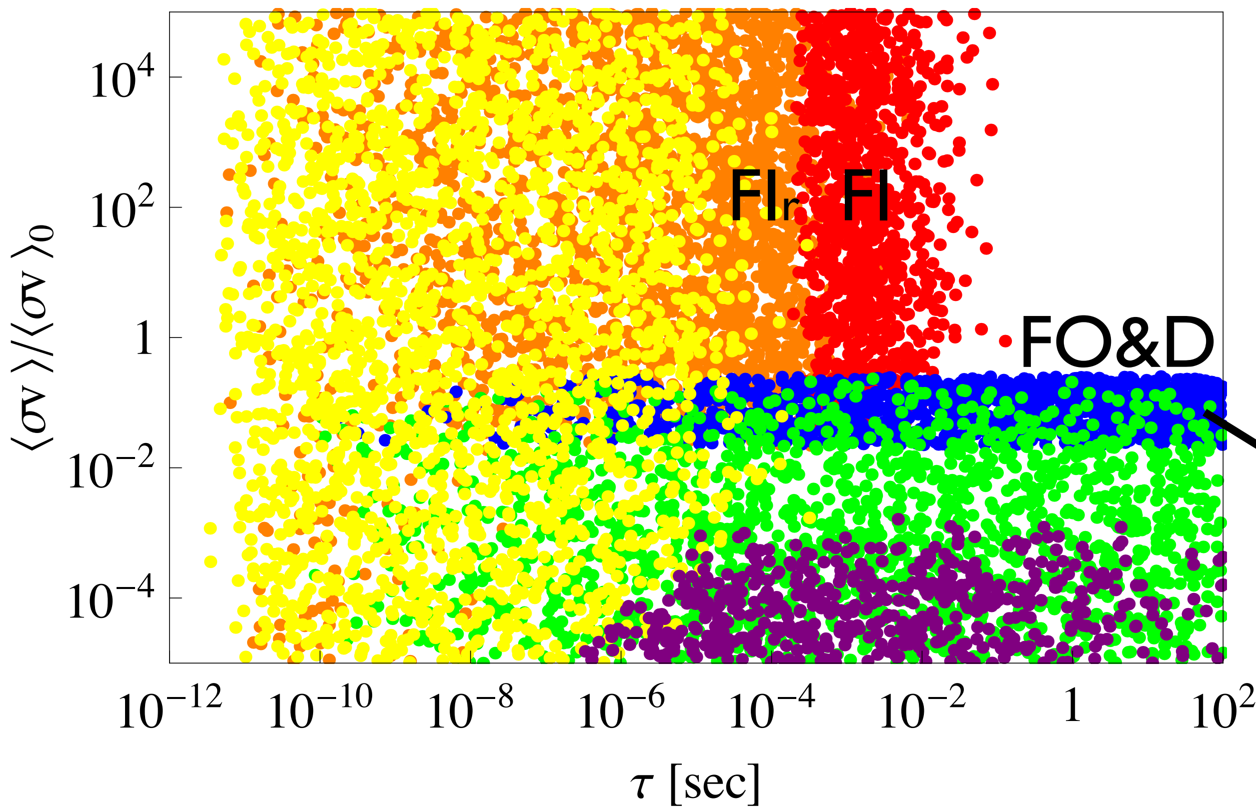

$$\frac{\langle \sigma v \rangle m}{m'} \sim \frac{4 \times 10^{10}}{M_{\rm Pl}\sqrt{g_\star}} \sim \frac{2 \times 10^{-25}\ \mathrm{cm^3 sec^{-1}}}{\sqrt{g_\star}}$$

$$L_{\rm FO\&D} \sim (10^{10} - 10^{-5}\ \mathrm{meters})\gamma$$

$10\ \mathrm{GeV} < m < 1\ \mathrm{TeV}$

$1/20 < m'/m < 1/2$

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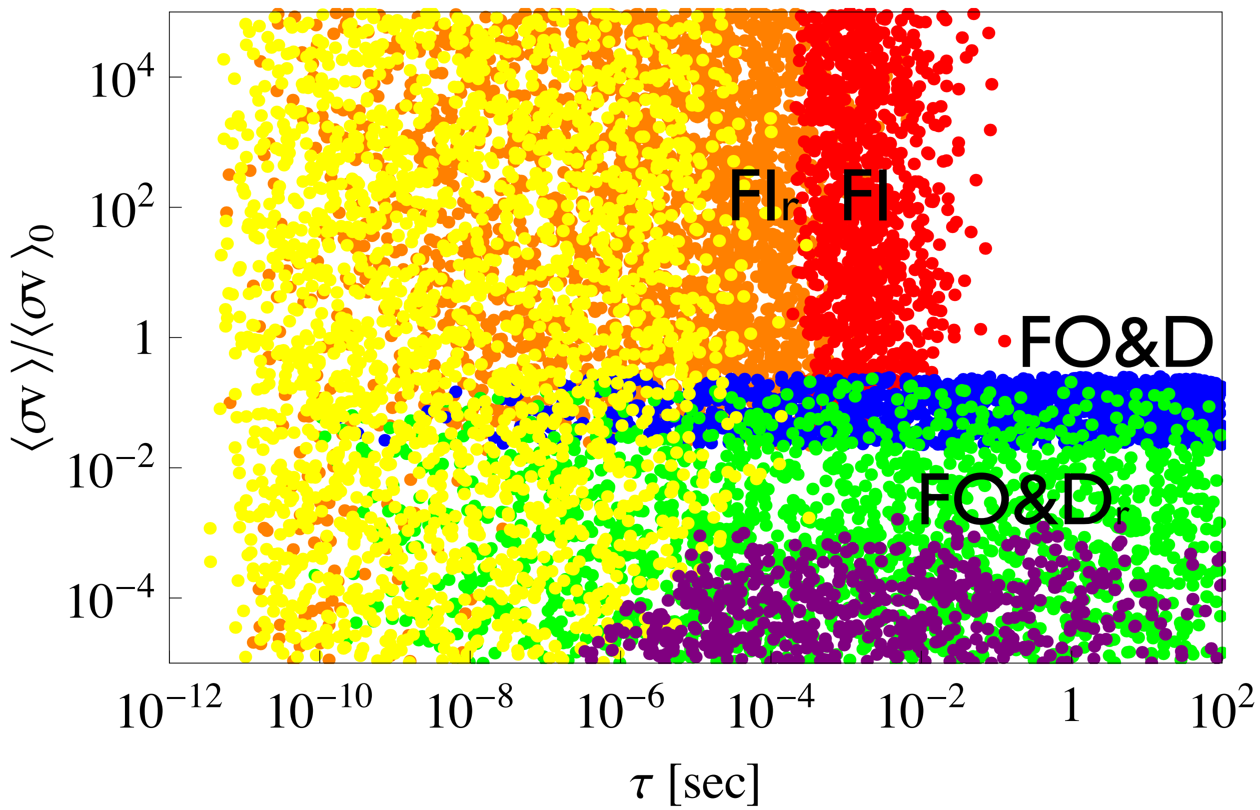

$$10 \text{ GeV} < m < 1 \text{ TeV}$$
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Getting the Right Relic Abundance

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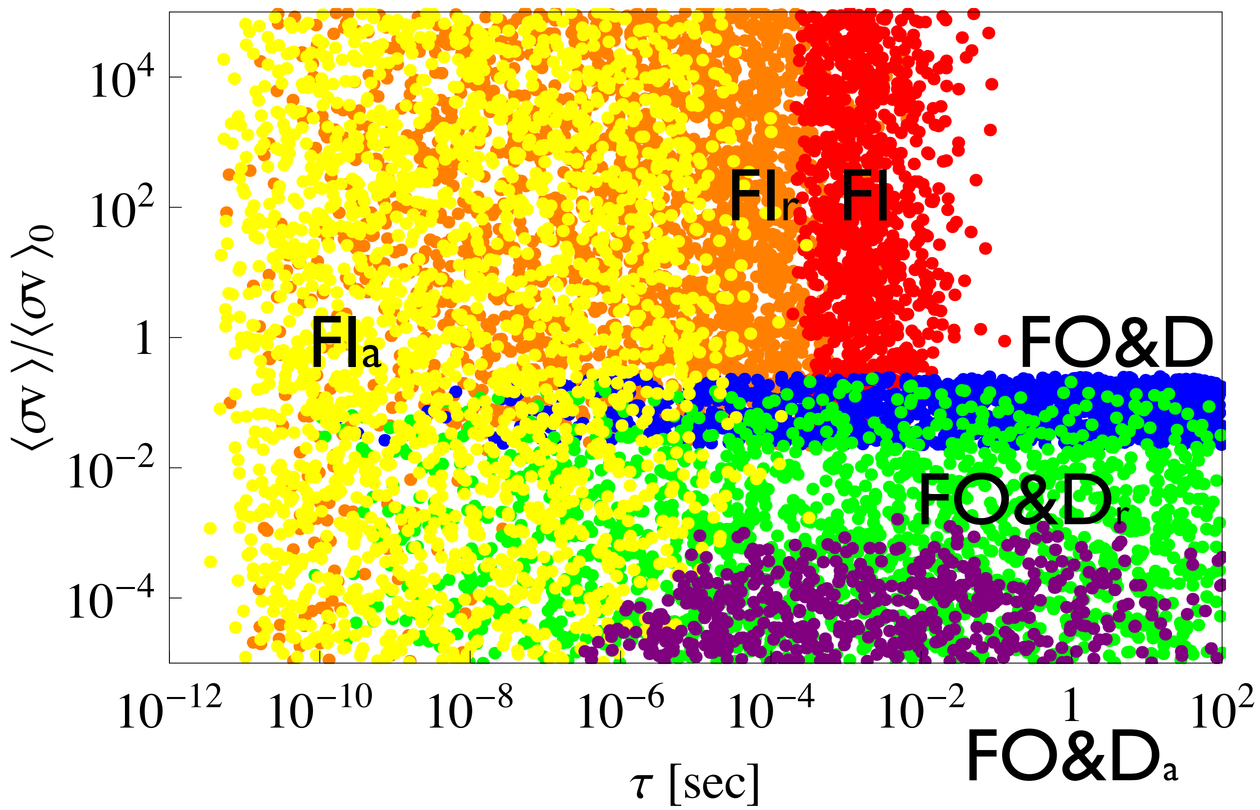
Production mechanisms map to distinct window in parameter



$10 \text{ GeV} < m < 1 \text{ TeV}$

$1/20 < m'/m < 1/2$

Generating Dark Matter

particle asy

$10^{-8} < \epsilon$

Yellow and Purple coor to getting the right DM abundance via particle anti-particle asym, which unlike FO and FO' you can do with FI and FO&D since sectors are thermally decoupled and

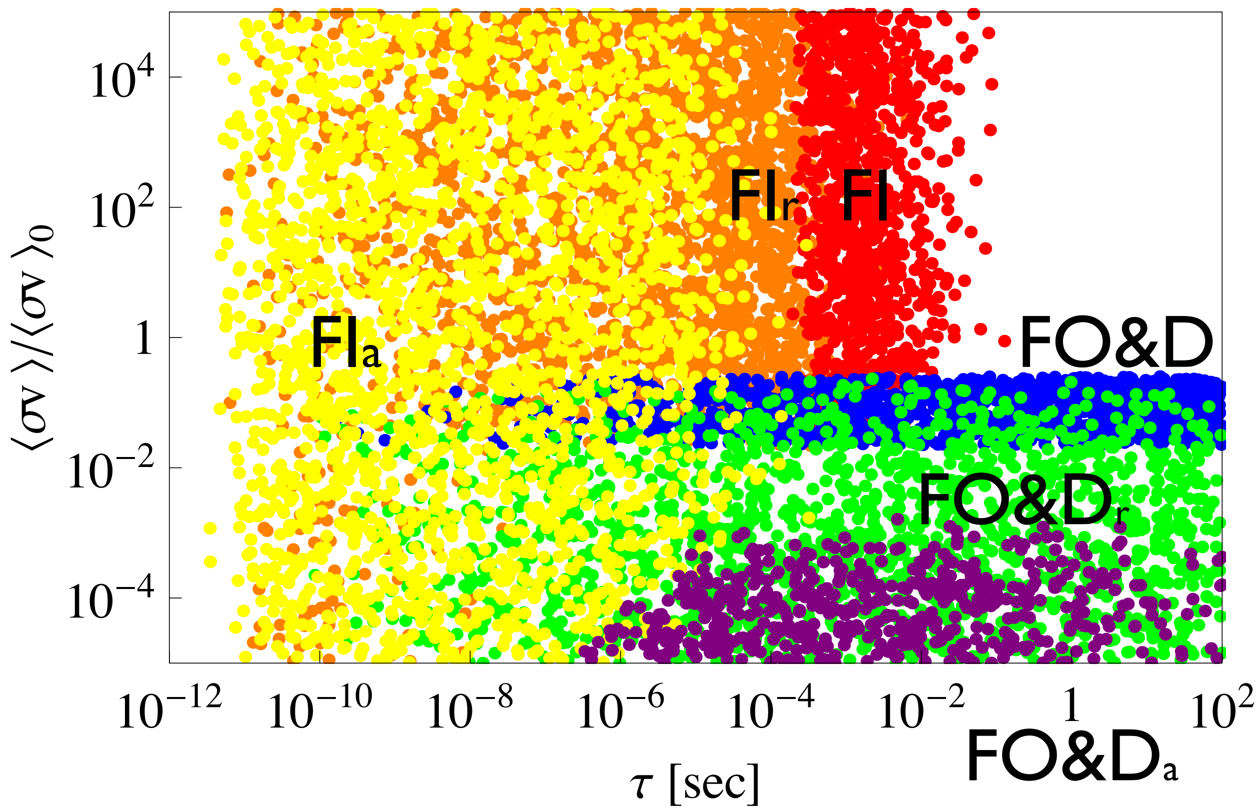
thus connector operators are not in TE. As usual we need to get rid of the symmetric part of the yield (since it is larger by a factor of 1/epsilon) which can happen if re-anhh are active to get rid

of symm component. Here we have scanned over epsilon the CP violation paramter.

Getting the Right Relic Abundance

$$\Omega_{DM} h^2 \sim 0.11$$

Production mechanisms map to distinct window in parameter space:



$10 \text{ GeV} < m < 1 \text{ TeV}$

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measure masses

Getting the Right Relic Abundance

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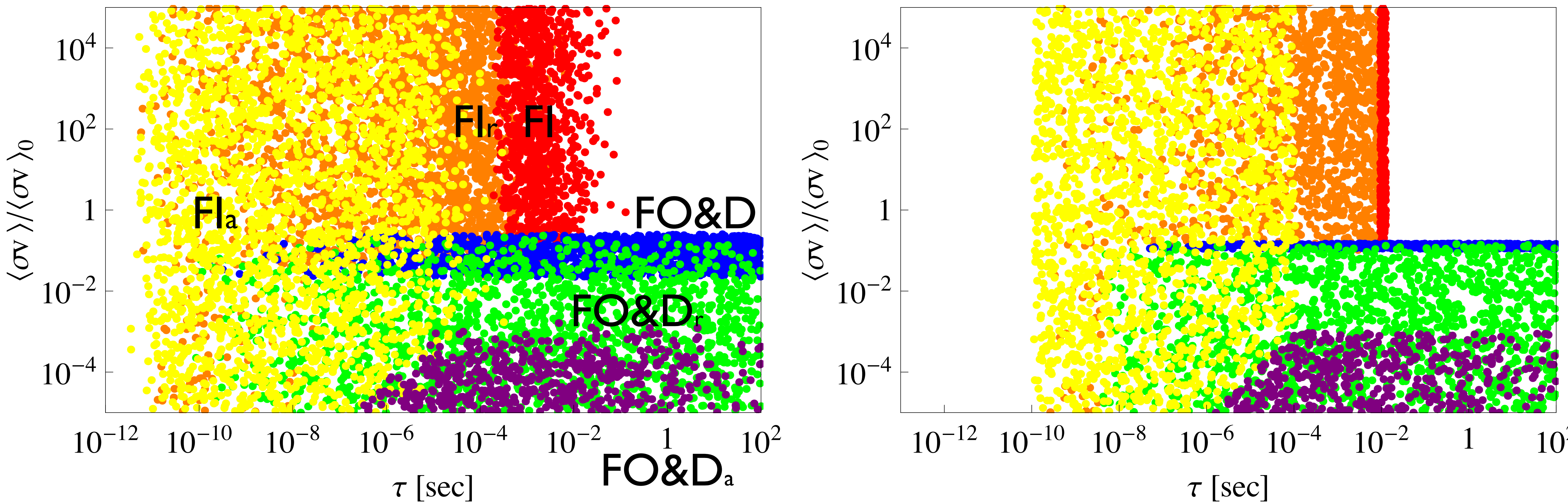


$10 \text{ GeV} < m < 1 \text{ TeV}$
$1/20 < m'/m < 1/2$

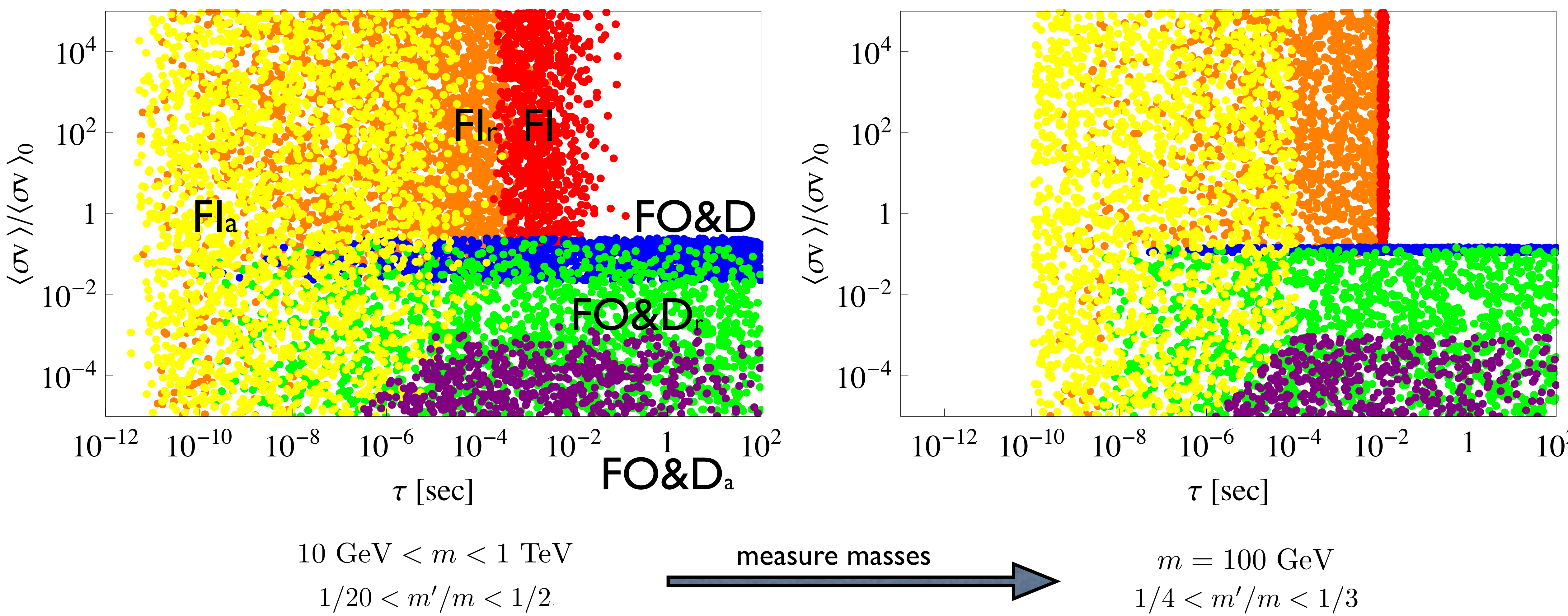
measure masses

$m = 100 \text{ GeV}$
$1/4 < m'/m < 1/3$

Getting the Right Relic Abundance

$$\Omega_{DM} h^2 \sim 0.11$$

Production mechanisms map to distinct window in parameter space:



Lifetime ranges are promising for seeing X decays within detectors.
To address "reconstruction" we must choose a more specific model.

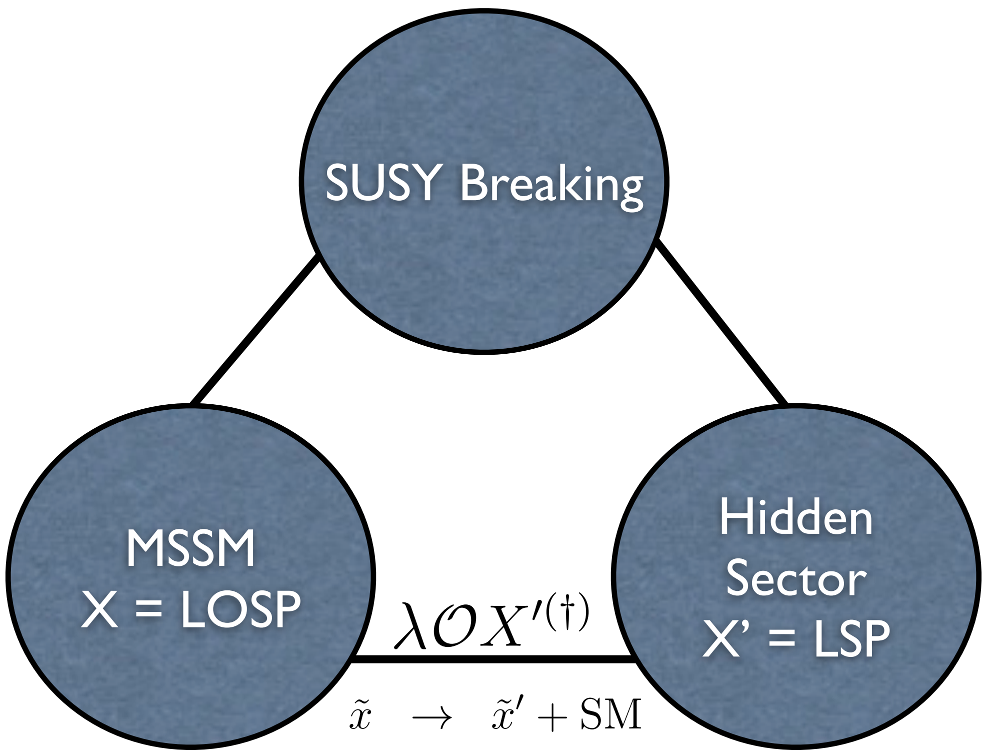
Collider Signals arXiv:1010.0024

II. Collider Physics

Supersymmetric Model

Assumptions:

- Visible sector is the MSSM, and X is the LOSP $X \in \{Q, U, D, L, E, H_u, H_d, B^\alpha, W^\alpha, G^\alpha\}$
- X' is the LSP and is stabilized by R-Parity
- X' is a SM gauge singlet.
- Hidden and visible sectors are connected by gauge invariant dimension five or lower operators. $\mathcal{O}X'^{(\dagger)}$



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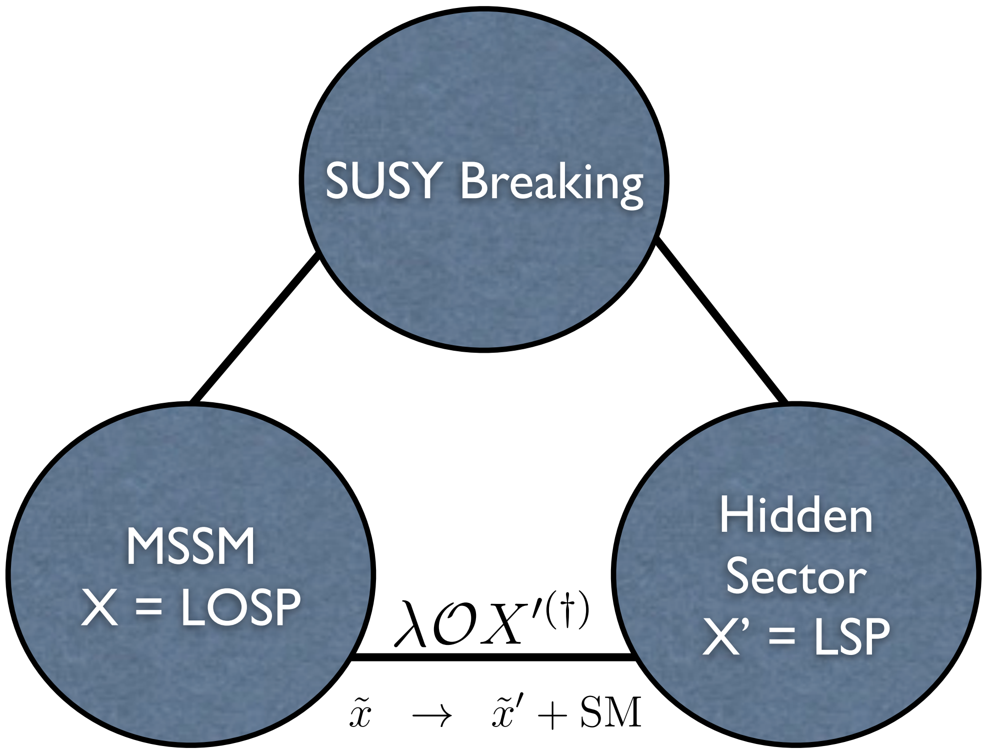

What are the possible Portal Operators?

Portal Operators

Choice of R-parity and R-charge of X' dictates which portal operators are allowed.

$$\mathcal{O}\, X'^{(\dagger)}$$

Gauge invariant dimension < 5 operator
Need not contain the LOSP!

Gauge singlet

Portal Operators

Choice of R-parity and R-charge of X' dictates which portal operators are allowed.

$$\mathcal{O}\,X'^{(\dagger)}$$

Gauge invariant dimension < 5 operator
Need not contain the LOSP!

Gauge singlet

	$\mathcal{O}_K$	$\mathcal{O}_W$	H_uH_d	B^α	LH_u	$LH_d^\dagger$	LLE, QLD	UDD
R-parity	$+$	$+$	$+$	$-$	$-$	$-$	$-$	$-$
R-charge	0	2	R_1	1	R_2	$R_2 - R_1$	$2 + R_2 - R_1$	R_3

$$\begin{aligned}
\mathcal{O}_K &= \{Q^\dagger Q, U^\dagger U, D^\dagger D, L^\dagger L, E^\dagger E, H_u^\dagger H_u, H_d^\dagger H_d\} \\
\mathcal{O}_W &= \{B^\alpha B_\alpha, W^\alpha W_\alpha, G^\alpha G_\alpha, QH_uU, QH_dD, LH_dE\}
\end{aligned}$$

Portal Operators

Choice of R-parity and R-charge of X' dictates which portal operators are allowed.

$$\mathcal{O}X'^{(\dagger)}$$

Present in the MSSM

	$\mathcal{O}_K$	$\mathcal{O}_W$	H_uH_d	B^α	LH_u	$LH_d^\dagger$	LLE, QLD	UDD
R-parity	$+$	$+$	$+$	$-$	$-$	$-$	$-$	$-$
R-charge	0	2	R_1	1	R_2	$R_2 - R_1$	$2 + R_2 - R_1$	R_3

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Portal Operators

Choice of R-parity and R-charge of X' dictates which portal operators are allowed.

$$\mathcal{O} X'^{(\dagger)}$$

Higgs Portal (mass mixing)

Bino Portal (Kinetic Mixing)

	$\mathcal{O}_K$	$\mathcal{O}_W$	$H_u H_d$	B^α	LH_u	$LH_d^\dagger$	LLE, QLD	UDD
R-parity	$+$	$+$	$+$	$-$	$-$	$-$	$-$	$-$
R-charge	0	2	R_1	1	R_2	$R_2 - R_1$	$2 + R_2 - R_1$	R_3

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\end{aligned}$$

Portal Operators

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$$\mathcal{O} X'^{(\dagger)}$$

X' with odd R parity can couple to RPV operators.

	$\mathcal{O}_K$	$\mathcal{O}_W$	$H_u H_d$	B^α	$L H_u$	$L H_d^\dagger$	LLE, QLD	UDD
R-parity	$+$	$+$	$+$	$-$	$-$	$-$	$-$	$-$
R-charge	0	2	R_1	1	R_2	$R_2 - R_1$	$2 + R_2 - R_1$	R_3

$$\begin{aligned} \mathcal{O}_K &= \{Q^\dagger Q, U^\dagger U, D^\dagger D, L^\dagger L, E^\dagger E, H_u^\dagger H_u, H_d^\dagger H_d\} \\ \mathcal{O}_W &= \{B^\alpha B_\alpha, W^\alpha W_\alpha, G^\alpha G_\alpha, Q H_u U, Q H_d D, L H_d E\} \end{aligned}$$

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Choice of R-parity and R-charge of X' dictates which portal operators are allowed.

$$\mathcal{O} X'^{(\dagger)}$$

	$\mathcal{O}_K$	$\mathcal{O}_W$	$H_u H_d$	B^α	$L H_u$	$L H_d^\dagger$	LLE, QLD	UDD
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R-charge	0	2	R_1	1	R_2	$R_2 - R_1$	$2 + R_2 - R_1$	R_3

Could be fixed if we want see-saw neutrino masses.

$$\begin{aligned}\mathcal{O}_K &= \{Q^\dagger Q, U^\dagger U, D^\dagger D, L^\dagger L, E^\dagger E, H_u^\dagger H_u, H_d^\dagger H_d\} \\ \mathcal{O}_W &= \{B^\alpha B_\alpha, W^\alpha W_\alpha, G^\alpha G_\alpha, QH_uU, QH_dD, LH_dE\}\end{aligned}$$

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Out of these which operators give the best hope of reconstruction for FO&D and for FI?

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Out of these which operators give the best hope of reconstruction for FO&D and for FI?

What are the possible LOSP candidates that are allowed and have the best hope of reconstruction at the LHC?

Reconstructing FO&D

To reconstruct need: $m, m', \langle \sigma v \rangle$

<u>LOSP Candidates:</u>

FO abundance of LOSP must be large enough:

$\Omega \propto \dfrac{m'}{m\langle \sigma v \rangle}$ $\Longrightarrow$ LOSP must overproduce by m/m'

Two LOSP candidates in the MSSM:

- Bino with $m_{\tilde{b}} < 250 \text{ GeV}$ $m'/m_{\tilde{b}} > 1/20$
- Slepton with $m_{\tilde{l}_R} > 700 \text{ GeV}$ $m'/m_{\tilde{l}_R} < 1/2$

$$X \in \{\cancel{Q}, \cancel{U}, \cancel{D}, \cancel{L}, E, \cancel{H}_u, \cancel{H}_d, B^\alpha, \cancel{W}^\alpha, \cancel{G}^\alpha\}$$

$$\mathcal{O}_K = \{Q^\dagger Q, U^\dagger U, D^\dagger D, L^\dagger L, E^\dagger E, H_u^\dagger H_u, H_d^\dagger H_d\}$$

$$\mathcal{O}_W = \{B^\alpha B_\alpha, W^\alpha W_\alpha, G^\alpha G_\alpha, QH_uU, QH_dD, LH_dE\}$$

Portal Operators:

No restrictions:

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Case of R-parity even LSP:

FO&D					
Operator	Charges (X')	$\tilde{\chi}_0$ Decay	$\tilde{\chi}_0$ k	$\tilde{\ell}^\pm$ Decay	$\tilde{\ell}^\pm$ k
$\mathcal{O}_K X'$	$(+,0)$	$\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	1
		$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$		
$\mathcal{O}_W X'$	$(+,0)$	$\chi_0 \to (\gamma, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{b}}, \theta^2_{\tilde{\chi}\tilde{w}}$	$\tilde{\ell}^\pm \to \ell^\pm(\gamma, Z)\tilde{x}'$	$\frac{1}{(4\pi)^2} m^2 (\frac{g^2_{1\ell}}{m^2_{\tilde{b}}}, \frac{g_2^2}{m^2_{\tilde{w}}})$
		$\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	1
H_uH_dX' $(X'^\dagger)$	$(+, 2 - R_1)$ or $(+, R_1)$	$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	$g^2_{\tilde{h}\tilde{\ell}\ell}$
		$\tilde{\chi}_0 \to y'\tilde{y}'$	$\theta^2_{\tilde{\chi}\tilde{h}} \lambda'^2$		
		$\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} g^2_{1\ell} \frac{m^4}{m^4_{\tilde{l}}}$		

$$\Gamma(\tilde{x} \to \tilde{x}' + \mathrm{SM}) = \left(\frac{1}{8\pi}\lambda^2 m\right) k(\tilde{x} \to \tilde{x}' + \mathrm{SM})$$

$$\mathcal{O}_K = \{Q^\dagger Q, U^\dagger U, D^\dagger D, L^\dagger L, E^\dagger E, H_u^\dagger H_u, H_d^\dagger H_d\}$$
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Portal Operators:

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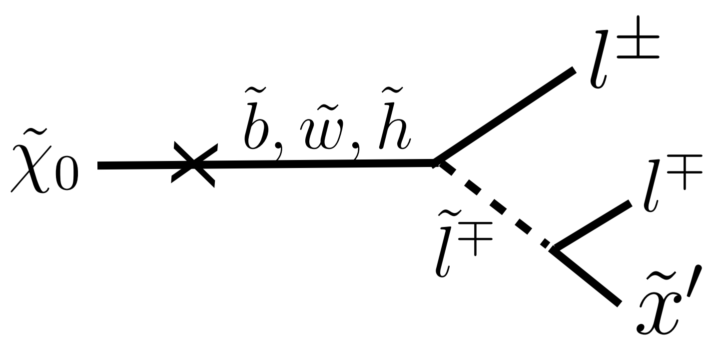

Case of R-parity even LSP:

FO&D					
		$\tilde\chi_0$		$\tilde\ell^\pm$	
Operator	Charges (X')	Decay	k	Decay	k
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		$\tilde\chi_0 \to (h^0, Z)\tilde x'$	$\theta^2_{\tilde\chi\tilde h}, \theta^2_{\tilde\chi\tilde h} g_2^2$		
$\mathcal{O}_W X'$	$(+,0)$	$\chi_0 \to (\gamma, Z)\tilde x'$	$\theta^2_{\tilde\chi\tilde b}, \theta^2_{\tilde\chi\tilde w}$	$\tilde\ell^\pm \to \ell^\pm(\gamma, Z)\tilde x'$	$\frac{1}{(4\pi)^2} m^2 (\frac{g^2_{1\ell}}{m^2_{\tilde b}}, \frac{g_2^2}{m^2_{\tilde w}})$
		$\tilde\chi_0 \to \ell^+\ell^-\tilde x'$	$\frac{1}{(4\pi)^2} g^2_{\tilde\chi\tilde\ell\ell}\frac{m^4}{m^4_{\tilde l}}$	$\tilde\ell^\pm \to \ell^\pm \tilde x'$	1
H_uH_dX' $(X'^\dagger)$	$(+, 2-R_1)$ or $(+, R_1)$	$\tilde\chi_0 \to (h^0, Z)\tilde x'$	$\theta^2_{\tilde\chi\tilde h}, \theta^2_{\tilde\chi\tilde h} g_2^2$	$\tilde\ell^\pm \to \ell^\pm \tilde x'$	$g^2_{\tilde h\tilde\ell\ell}$
		$\tilde\chi_0 \to y'\tilde y'$	$\theta^2_{\tilde\chi\tilde h}\lambda'^2$		
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Portal Operators:

No restrictions:

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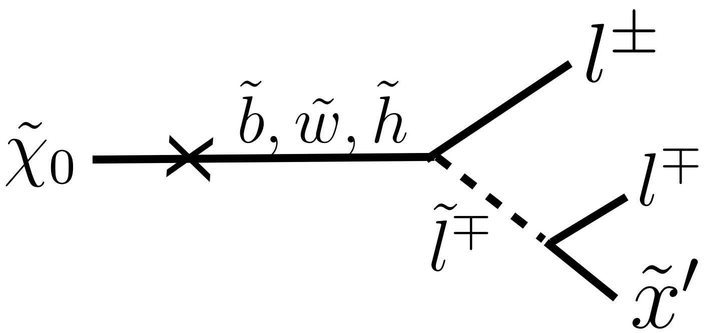

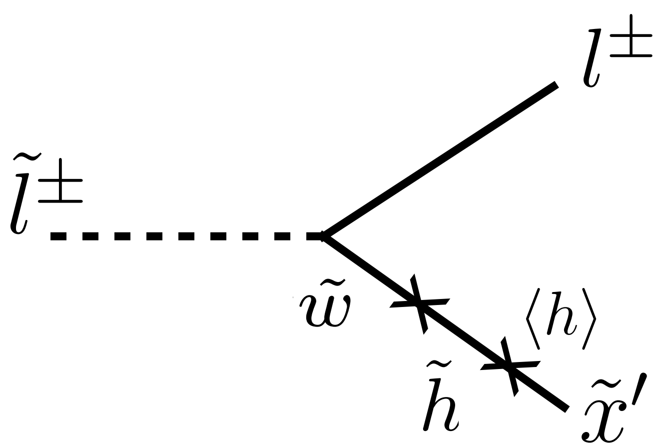

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		$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$		
$\mathcal{O}_W X'$	$(+,0)$	$\chi_0 \to (\gamma, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{b}}, \theta^2_{\tilde{\chi}\tilde{w}}$	$\tilde{\ell}^\pm \to \ell^\pm(\gamma, Z)\tilde{x}'$	$\frac{1}{(4\pi)^2} m^2 (\frac{g^2_{1\ell}}{m^2_{\tilde{b}}}, \frac{g_2^2}{m^2_{\tilde{w}}})$
		$\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	1
H_uH_dX' $(X'^\dagger)$	$(+, 2-R_1)$ or $(+, R_1)$	$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	$g^2_{\tilde{h}\tilde{\ell}\ell}$
		$\tilde{\chi}_0 \to y'\tilde{y}'$	$\theta^2_{\tilde{\chi}\tilde{h}} \lambda'^2$		
		$\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} g^2_{1\ell} \frac{m^4}{m^4_{\tilde{l}}}$		

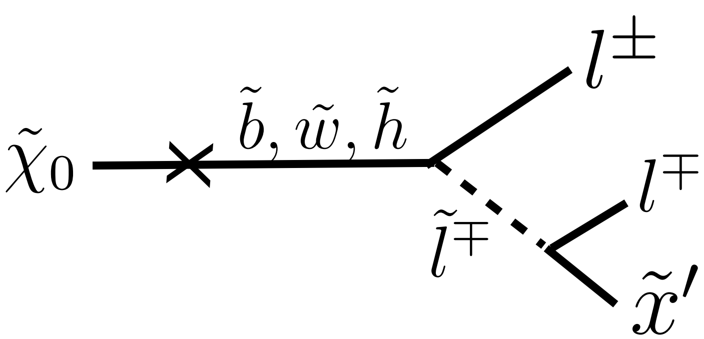
$$\Gamma(\tilde{x} \to \tilde{x}' + \mathrm{SM}) = \left(\frac{1}{8\pi}\lambda^2 m\right) k(\tilde{x} \to \tilde{x}' + \mathrm{SM})$$

$$\mathcal{O}_K = \{Q^\dagger Q, U^\dagger U, D^\dagger D, L^\dagger L, E^\dagger E, H_u^\dagger H_u, H_d^\dagger H_d\}$$
$$\mathcal{O}_W = \{B^\alpha B_\alpha, W^\alpha W_\alpha, G^\alpha G_\alpha, QH_uU, QH_dD, LH_dE\}$$

<u>Portal Operators:</u>

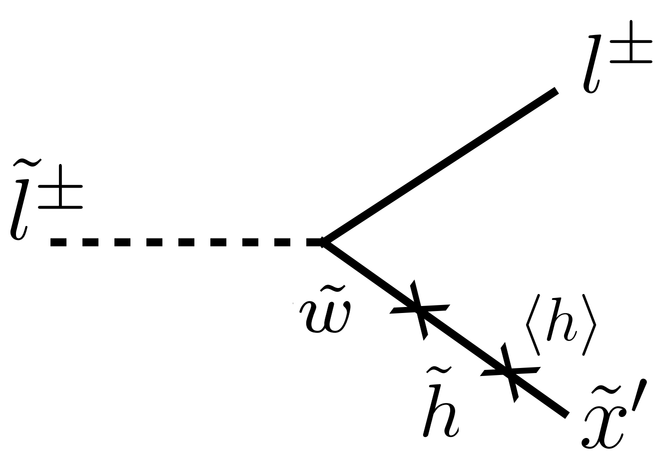
No restrictions:

	$\mathcal{O}_K$	$\mathcal{O}_W$	H_uH_d	B^α	LH_u	$LH_d^\dagger$	LLE, QLD	UDD
R-parity	$+$	$+$	$+$	$-$	$-$	$-$	$-$	$-$
R-charge	0	2	R_1	1	R_2	$R_2 - R_1$	$2 + R_2 - R_1$	R_3



Case of R-parity even LSP:

FO&D					
		$\tilde{\chi}_0$		$\tilde{\ell}^\pm$	
Operator	Charges (X')	Decay	k	Decay	k
$\mathcal{O}_K X'$	$(+,0)$	$\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	1
		$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$		
$\mathcal{O}_W X'$	$(+,0)$	$\chi_0 \to (\gamma, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{b}}, \theta^2_{\tilde{\chi}\tilde{w}}$	$\tilde{\ell}^\pm \to \ell^\pm(\gamma, Z)\tilde{x}'$	$\frac{1}{(4\pi)^2} m^2 (\frac{g^2_{1\ell}}{m^2_{\tilde{b}}}, \frac{g_2^2}{m^2_{\tilde{w}}})$
		$\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	1
H_uH_dX' $(X'^\dagger)$	$(+, 2-R_1)$ or $(+, R_1)$	$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	$g^2_{\tilde{h}\tilde{\ell}\ell}$
		$\tilde{\chi}_0 \to y'\tilde{y}'$	$\theta^2_{\tilde{\chi}\tilde{h}} \lambda'^2$		
		$\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} g^2_{1\ell} \frac{m^4}{m^4_{\tilde{l}}}$		



Portal coupling need not contain the LOSP!

$$\Gamma(\tilde{x} \to \tilde{x}' + \mathrm{SM}) = \left(\frac{1}{8\pi}\lambda^2 m\right) k(\tilde{x} \to \tilde{x}' + \mathrm{SM})$$

Reconstructing FI

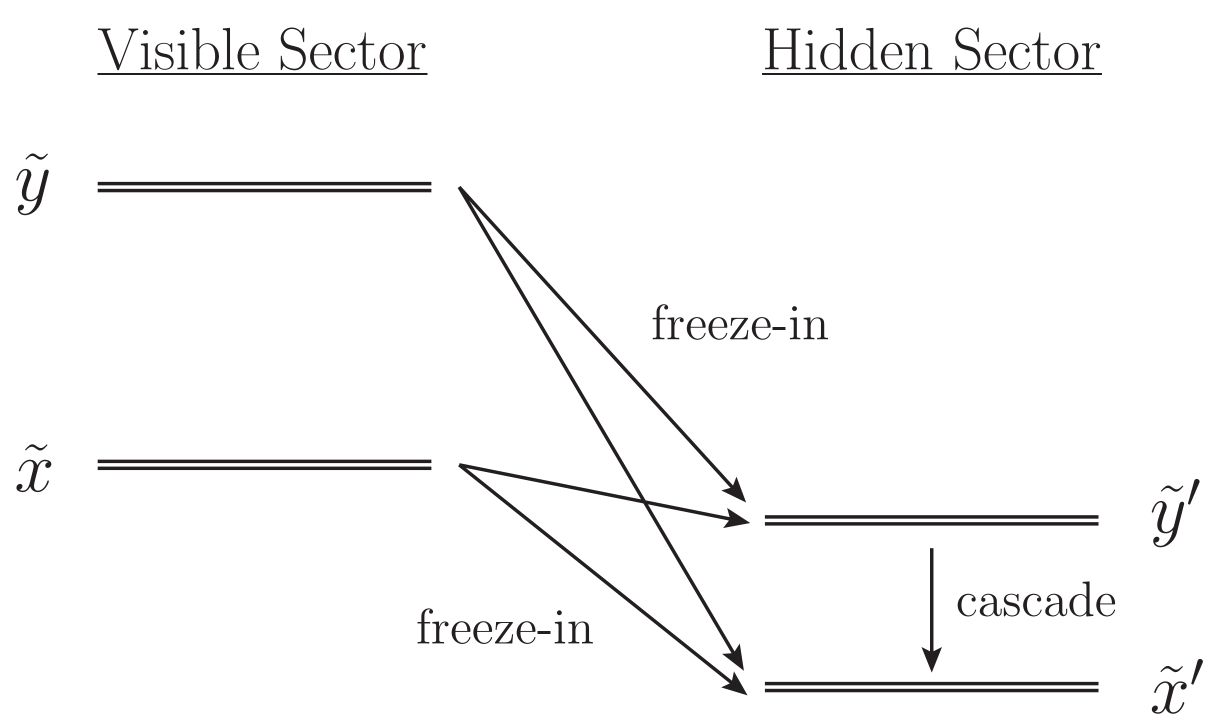
To reconstruct: m, m', τ * Unlike FO&D it is conceivable to directly measure all three at colliders

LOSP Candidates:

FO abundance must be small → Only bino excluded

Portal Operators:

Hidden Sector is rich, additional fields can give a FI contribution to X $\Omega \propto \frac{m'}{m^2 \tau}$



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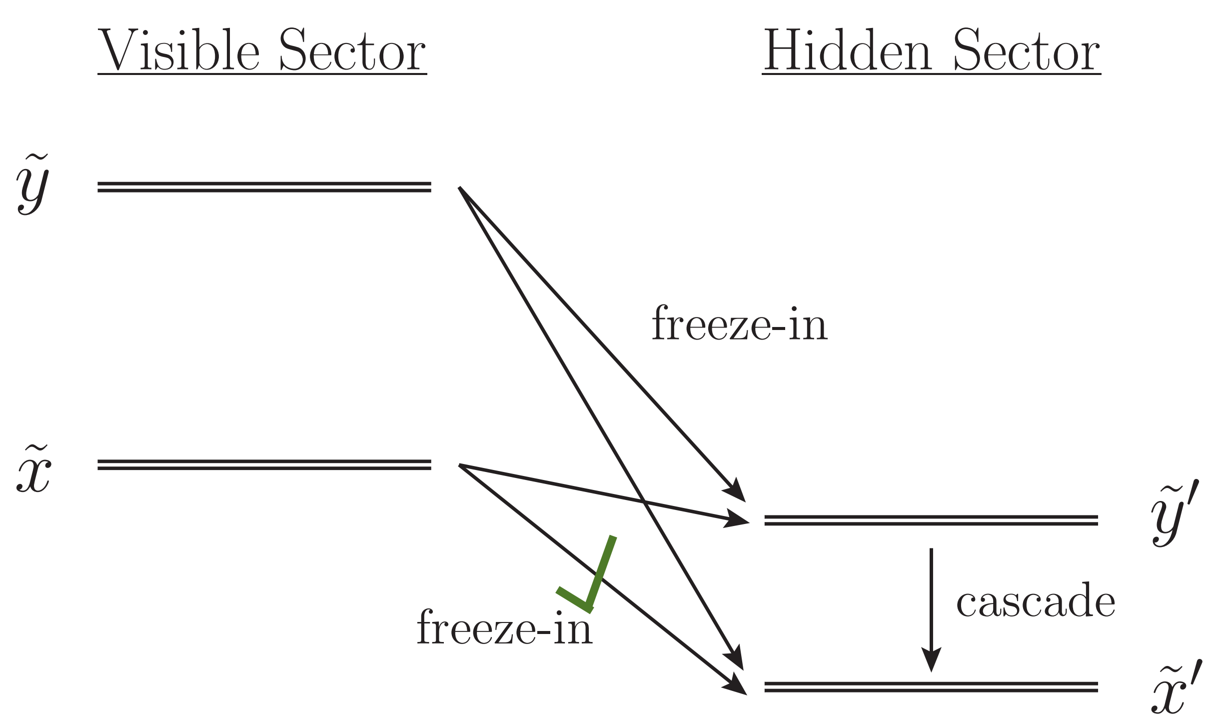


Reconstructing FI

To reconstruct: m, m', τ * Unlike FO&D it is conceivable to directly measure all three at colliders

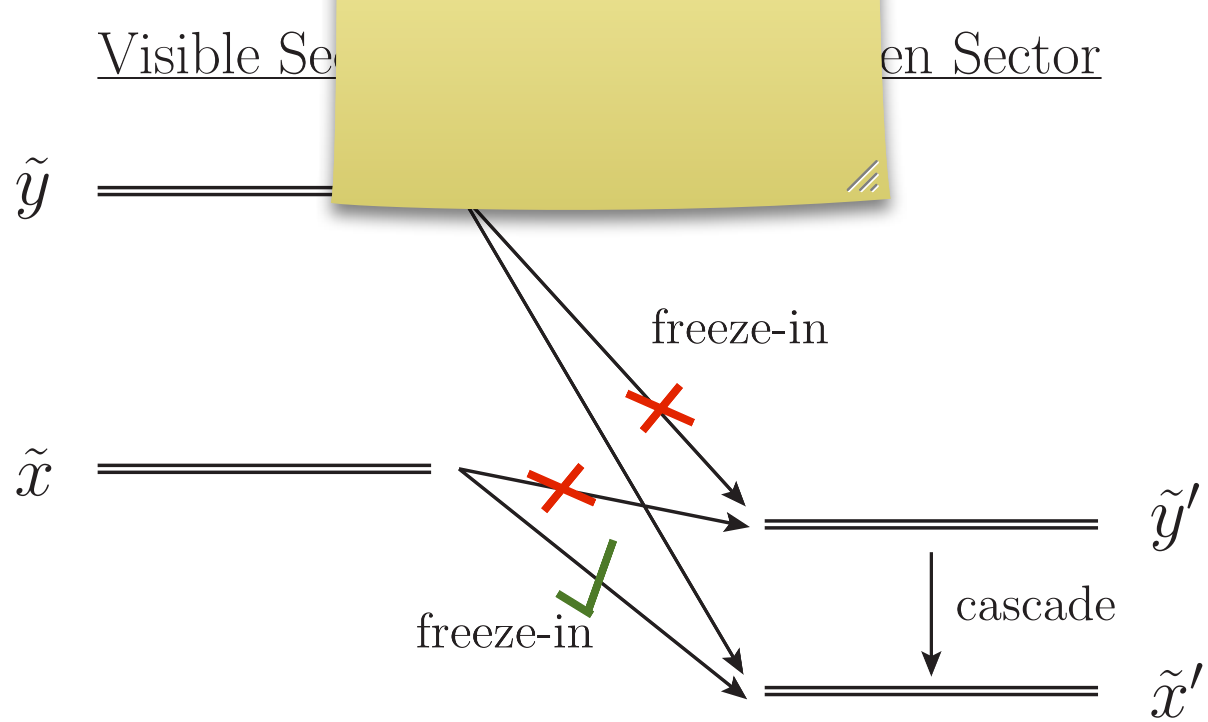
<u>LOSP Candidates:</u>

FO abundance must be small → Only bino excluded

<u>Portal Operators:</u>

Hidden Sector is rich, additional field ... tion to X $\Omega \propto \frac{m'}{m^2\tau}$

No hope of recon because they depend on hidden sector couplings. Hope they are forbidden by symmetries.



Reconstructing FI

To reconstruct: m, m', τ * Unlike FO&D it is conceivable to directly measure all three at colliders

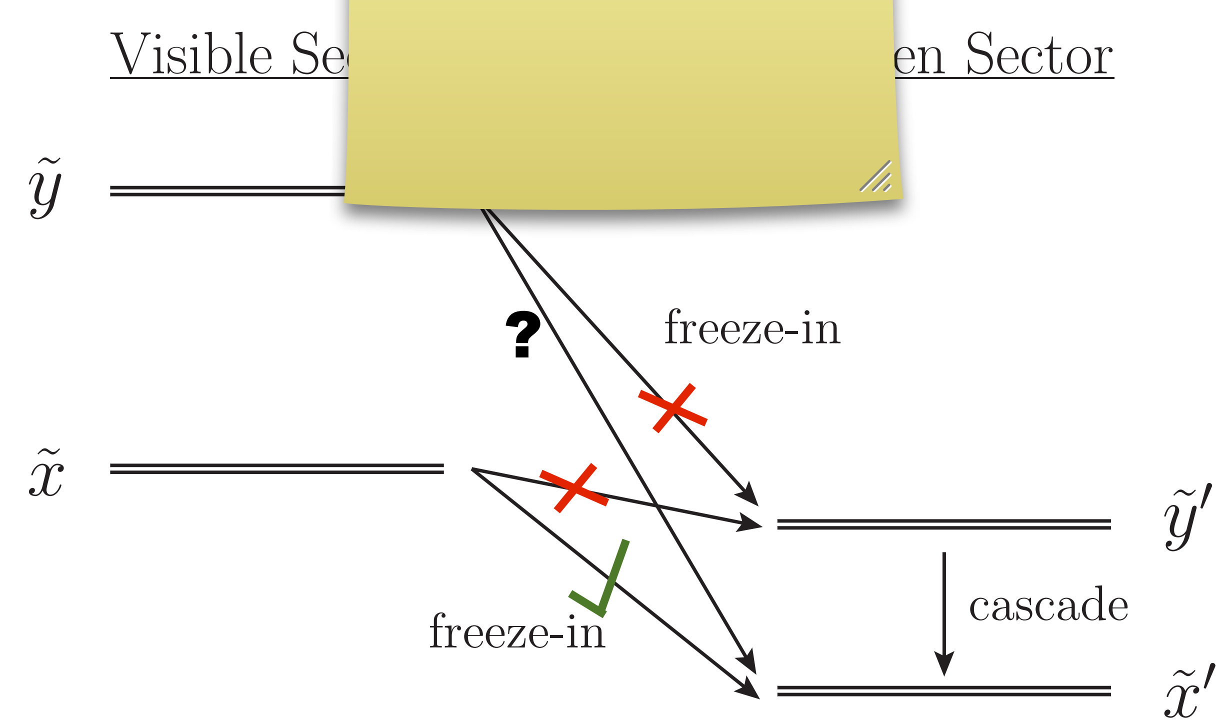
LOSP Candidates:

FO abundance must be small → Only bino excluded

Portal Operators:

FI of LSP by non-LOSP
Can we recon???

Hidden Sector is rich, additional field ... tion to X $\Omega \propto \frac{m'}{m^2\tau}$



Any hope? $\tilde{y} \to \tilde{x}' + \mathrm{SM}$

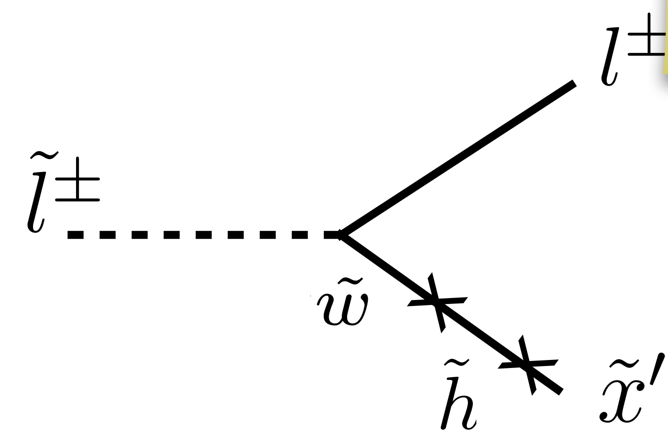
If only one operator couples the visible and hidden sectors then the coupling for FI of non-LOSPs can be inferred from the FI on the LOSP.

$\tilde{x} \rightarrow \tilde{x}' + \mathrm{SM}$

True also for LH, however L carries flavor index so that amount of couplings we would have to measure is considerably more so we don't consider this here

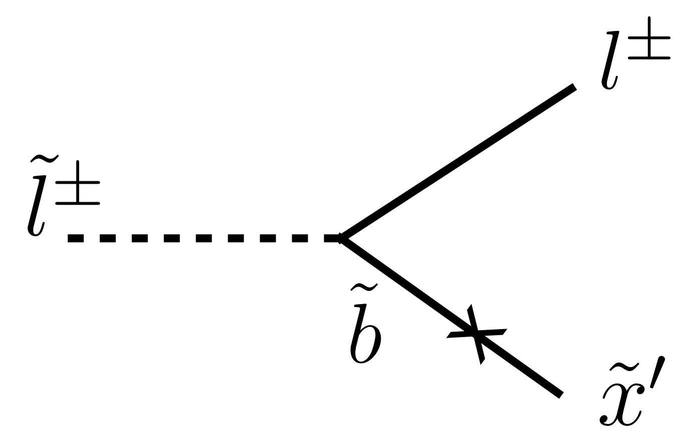
	$\mathcal{O}_K$	$\mathcal{O}_W$	$H_u H_d$	B^α	LH_u	$LH_d^\dagger$	LLE, QLD	UDD
R-parity	$+$	$+$	$+$	$-$	$-$	$-$	$-$	$-$
R-charge	0	2	R_1	1	R_2	$R_2 - R_1$	$2 + R_2 - R_1$	R_3

- Higgs Portal: $\lambda \int d^2\theta\, H_u H_d X'$



Mixing higgsino and dark matter though Higgs VEV.

- Bino Portal: $\lambda \int d^2\theta\, B^\alpha X'_\alpha$



Kinetic Mixing of bino and dark matter

Need to measure everything...

*The portal coupling may be extracted from the slepton lifetime and measurement of the neutralino mass matrix.

* Measure SUSY spectrum and compute the yield of DM from FI from decays of other superpartners.

*These yields will differ for the Higgs and Bino portals.

Conclusions

- A thermally decoupled hidden sector provides seven dark matter production mechanisms:

  FO' FO&D FO&D$_r$ FO&D$_a$ FI FI$_r$ FI$_a$

- Freeze-out and Decay and Freeze-In have correspond to distinctive windows in parameter space and depend only on quantities that could in principle be measured at colliders.

	Freeze-Out and Decay (FO&D)	Freeze-In (FI)
LOSP	$\tilde{\chi}_0, \tilde{\ell}$	$\tilde{q},\ \tilde{\ell},\ \tilde{\nu},\ \tilde{g},\ \tilde{\chi}_0,\ \tilde{\chi}_\pm$
Operators	$\mathcal{O}X'$	$H_u H_d X',\ B^\alpha X'_\alpha$
Observables	$m, m', \langle\sigma v\rangle$	m, m', τ
Range	$10^{-27}\ \mathrm{cm}^3/\mathrm{s} < \langle\sigma v\rangle < 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$	$10^{-4}\ \mathrm{s} < \tau < 10^{-1}\ \mathrm{s}$
Predicted Relation	$\frac{m'\langle\sigma v\rangle_0}{m\langle\sigma v\rangle} = 1$	$\frac{m'}{m\tau}\left(\frac{100\ \mathrm{GeV}}{m}\right) = 25\ \mathrm{s}^{-1}$

Back Up Slides

Asymmetric $\mathrm{FI_a}$ and $\mathrm{FO\&D_a}$

We have been assuming that DM abundance arises from the symmetric yield: $Y' = (n' + \bar{n}')/s$ since $\bar{n} = n$

Given no asymmetry at high temperature what conditions are necessary for DM to arise from a particle anti-particle asymmetry? $\eta' = \dfrac{n' - \bar{n}'}{s}$

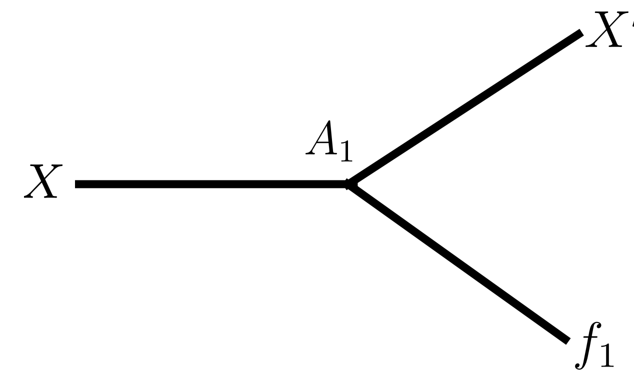
- X number violation requires hidden sector to contain a global $U(1)_X$
- X decays must be CP violating requires multiple X decay channels
- → Loss of thermal equilibrium

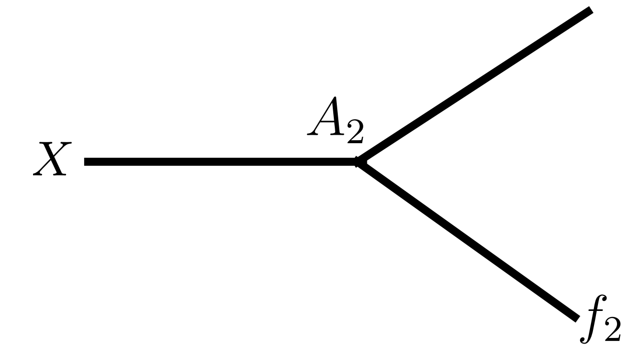
Asymmetry cannot be generated via FO or FO' since the total annihilation cross section is the same for particles and anti-particles by CPT.

Is it possible generate a non-zero asymmetry via FI and FO&D?

Yes! Sectors are at different temperatures so processes mediated by connector interactions are NOT in thermal equilibrium.

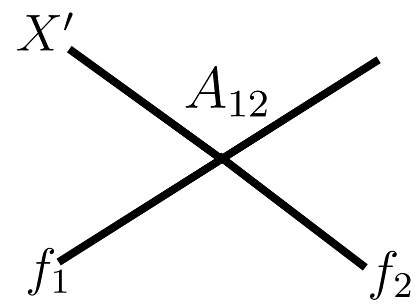
To violate CP requires multiple decay modes for X:





$U(1)_X$ Broken by connector operator

As well as a re-scattering vertex:



A non-zero CP violation in X decays results from the interference between tree and loop contributions to decays:

$$\epsilon \simeq \frac{1}{16\pi} \frac{\mathrm{Im}(A_1 A_2^* A_{12})}{|A_1|^2 + |A_2|^2}$$

From the Boltzmann equations: $\eta' = \epsilon Y'$

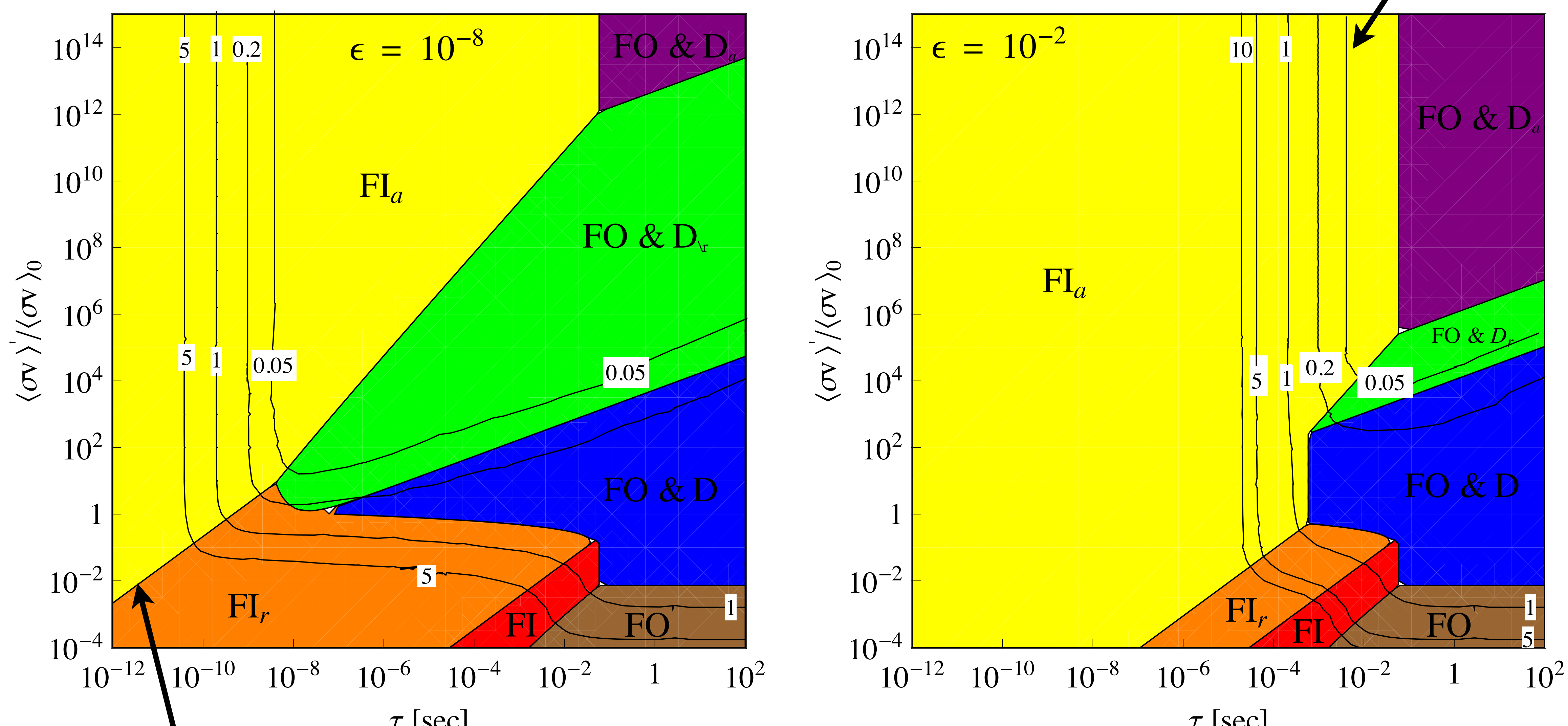
Since the asymmetric yield is suppressed relative to the symmetric yield in order for the asymmetric yield to dominate the Dark Matter re-annihilations must be active in order to diminish the symmetric yield.

To get the right relic abundance: $m'\eta' = 4 \times 10^{-10}$ GeV

Asymmetric Phase Diagrams

Contours of symmetric + asymmetric contributions:

Like FI without re-annihilations



Dominate when re-annihilations is maximal

$$Y'_{\text{FO\&D}} \propto \frac{1}{m\langle\sigma v\rangle} \qquad Y'_{\text{FI}} \propto \frac{1}{\tau m^2}$$

$$\langle\sigma v\rangle = \langle\sigma v\rangle_0 = 3\times10^{-26}\ \text{cm}^3/\text{s}$$
$$m = 100\,\text{GeV},\ m' = 50\,\text{GeV}$$
$$\xi_{\text{UV}} = 0.01$$

Collider Signatures of FO&D:

- Higgs or Bino Portals: The dominant decay will be 2-body into hidden sector states.

$$\lambda \int d^2\theta \, B^\alpha X'_\alpha$$

$$\mathcal{L}_{\rm int} \approx \lambda \left(\tilde{x}' \tilde{J} + \tilde{b} \tilde{J}' \right)$$

$$\tilde{J}' = \sum\nolimits_{\rm i=hidden} g'_i \phi'_i \psi'_i$$

$$\Rightarrow \quad \tilde{\chi}^0 \to y' \tilde{y}'$$

So LSP mass must be reconstructed from subdominant visible decay modes.

- LSP Multiplicities: Hidden sector states will cascade down and can produce an odd number of LSPs.

$$y' \to \tilde{x}' \tilde{x}'$$

X' is R-Parity Even

FO&D					
		$\tilde{\chi}_0$		$\tilde{\ell}^\pm$	
Operator	Charges (X')	Decay	k	Decay	k
$\mathcal{O}_K X'$	$(+,0)$	$\tilde{\chi}_0 \to \ell^+ \ell^- \tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	1
		$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$		
$\mathcal{O}_W X'$	$(+,0)$	$\chi_0 \to (\gamma, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{b}}, \theta^2_{\tilde{\chi}\tilde{w}}$	$\tilde{\ell}^\pm \to \ell^\pm (\gamma, Z)\tilde{x}'$	$\frac{1}{(4\pi)^2} m^2 (\frac{g^2_{1\ell}}{m^2_{\tilde{b}}}, \frac{g^2_2}{m^2_{\tilde{w}}})$
		$\tilde{\chi}_0 \to \ell^+ \ell^- \tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	1
$H_u H_d X'$ $(X'^\dagger)$	$(+, 2-R_1)$ or $(+, R_1)$	$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	$g^2_{\tilde{h}\tilde{\ell}\ell}$
		$\tilde{\chi}_0 \to y' \tilde{y}'$	$\theta^2_{\tilde{\chi}\tilde{h}} \lambda'^2$		
		$\tilde{\chi}_0 \to \ell^+ \ell^- \tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} g^2_{1\ell} \frac{m^4}{m^4_{\tilde{l}}}$		

X' is R-Parity Odd

FO&D					
		$\tilde{\chi}_0$		$\tilde{\ell}^\pm$	
Operator	Charges (X')	Decay	k	Decay	k
$B^\alpha X'_\alpha$	$(-,1)$	$\tilde{\chi}_0 \to y' \tilde{y}'$	$\theta^2_{\tilde{\chi}\tilde{b}} g'^2$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	$g^2_{1\ell}$
		$\tilde{\chi}_0 \to \ell^+ \ell^- \tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} g^2_{1\ell} \frac{m^4}{m^4_{\tilde{l}}}$		
		$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$		
$L H_u X'$	$(-, 2-R_2)$	$\tilde{\chi}_0 \to \nu \tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}$	$\tilde{\ell}^\pm \to \ell^\pm \nu \tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{h}\tilde{\ell}\ell} \frac{m^2}{m^2_{\tilde{h}}}$
		$\tilde{\chi}_0 \to \ell^\pm (h^\mp, W^\mp)\tilde{x}'$	$\frac{1}{(4\pi)^2} g_2^2 \frac{m^2}{m^2_{\tilde{h}}} (\theta^2_{\tilde{\chi}\tilde{w}}, \theta^2_{\tilde{\chi}\tilde{h}})$	$\tilde{\ell}^\pm \to (h^\pm, W^\pm)\tilde{x}'$	$\theta^2_{\tilde{\ell}\tilde{\ell}_L} (1, g_2^2)$
$L H_u X'^\dagger$	$(-, R_2)$	"	"	"	"
$L H_d^\dagger X'^\dagger$	$(-, R_2 - R_1)$	"	"	"	"
$L H_d^\dagger X'$	$(-, R_1 - R_2)$	"	"	"	"
$LLEX', QLDX'$	$(-, R_1 - R_2)$	$\tilde{\chi}_0 \to l^+ l^- \nu \tilde{x}'$	$\frac{1}{(4\pi)^4} g^2_{\tilde{\chi}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\ell}^\pm \to \ell^\pm \nu \tilde{x}'$	$\frac{1}{(4\pi)^2}$

Collider Signatures of FI:

FI				
	Higgs Portal: $H_u H_d X'$		Bino Portal: $B^\alpha X'_\alpha$	
LOSP	Decay	k	Decay	k
$\tilde g$	$\tilde g \to q q \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{\tilde h \tilde q q} \frac{m^4}{m^4_{\tilde q}}$	$\tilde g \to q q \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{1q} \frac{m^4}{m^4_{\tilde q}}$
$\tilde\nu$	$\tilde\nu \to \ell^\pm (h^\mp, W^\mp) \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{\tilde h \tilde\nu \ell} \frac{m^2}{m^2_{\tilde h}} (1, g_2^2)$	$\tilde\nu \to \ell^\pm (h^\mp, W^\mp) \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{1h} g^2_{\tilde h \tilde\nu \ell} \frac{m^2}{m^2_{\tilde h}} (1, g_2^2)$
	$\tilde\nu \to \tilde\nu \tilde x'$	$g^2_{\tilde h \tilde\nu \nu}$	$\nu \to \nu \tilde x'$	$g^2_{1\nu}$
$\tilde q$	$\tilde q \to q \tilde x'$	$g^2_{\tilde h \tilde q q}$	$\tilde q \to q \tilde x'$	g^2_{1q}
	$\tilde q \to q (h^{0,\pm}, W^{0,\pm}) \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{\tilde h \tilde q q} \frac{m^2}{m^2_{\tilde h}} (1, g_2^2)$	$\tilde q \to q (h^{0,\pm}, W^{0,\pm}) \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{1h} g^2_{\tilde h \tilde q q} \frac{m^2}{m^2_{\tilde h}} (1, g_2^2)$
$\tilde\chi^\pm$	$\tilde\chi^\pm \to (h^\pm, W^\pm) \tilde x'$	$g_2^2 (\theta^2_{\tilde\chi \tilde w}, \theta^2_{\tilde\chi \tilde h})$	$\tilde\chi^\pm \to (h^\pm, W^\pm) \tilde x'$	$g^2_{1h} (\theta^2_{\tilde\chi \tilde h}, \theta^2_{\tilde\chi \tilde w})$
	$\tilde\chi^\pm \to \ell^\pm \nu \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{\tilde\chi \tilde\ell \nu} g^2_{\tilde h \tilde\ell \ell} \frac{m^4}{m^4_{\tilde l}}$	$\tilde\chi^\pm \to \ell^\pm \nu \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{\tilde\chi \tilde\ell \nu} g^2_{1\ell} \frac{m^4}{m^4_{\tilde l}}$
$\tilde\chi_0$	$\tilde\chi_0 \to (h^0, Z) \tilde x'$	$\theta^2_{\tilde\chi \tilde h}, \theta^2_{\tilde\chi \tilde h} g_2^2$	$\tilde\chi_0 \to (h^0, Z) \tilde x'$	$\theta^2_{\tilde\chi \tilde h}\, g^2_{1h}, \theta^2_{\tilde\chi \tilde h} g_2^2 g^2_{1h}$
	$\tilde\chi_0 \to y' \tilde y'$	$\theta^2_{\tilde\chi \tilde h} \lambda'^2$	$\tilde\chi_0 \to y' \tilde y'$	$\theta^2_{\tilde\chi \tilde b} g'^2$
	$\tilde\chi_0 \to \ell^+ \ell^- \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{\tilde\chi \tilde\ell \ell} g^2_{\tilde h \tilde\ell \ell} \frac{m^4}{m^4_{\tilde l}}$	$\tilde\chi_0 \to \ell^+ \ell^- \tilde x'$	$\frac{1}{(4\pi)^2} g^2_{\chi \tilde\ell \ell} g^2_{1\ell} \frac{m^4}{m^4_{\tilde l}}$
$\tilde\ell^\pm$	$\tilde\ell^\pm \to \ell^\pm \tilde x'$	$g^2_{\tilde h \tilde\ell \ell}$	$\tilde\ell^\pm \to \ell^\pm \tilde x'$	$g^2_{1\ell}$

Collider Signals

Note: Asymmetric FI and FO&D are harder to reconstruct due to the CP phase but the same operators and LOSPs apply

- See signal at LHC.
- Identity of LOSP candidate is now known.
- What mechanism and what operator?
- Look up corresponding portal operator(s).
- Sometimes result is unique.
- How to resolve ambiguities?

X' is R-Parity Even

	$L^\dagger L X'$ $Q^\dagger Q X'$ $H^\dagger H X'$	$W^2 X'$	$QUHX'$ $LEHX'$ $QDHX'$	$H_u H_d X'$
$\tilde{\chi}^0$	$h^0, Z, \ell^+\ell^-$	$\gamma,\ Z$	l^+l^-	h^0, Z, l^+l^-
$\tilde{l}^\pm$	$l^\pm$	$l^\pm\left(\gamma, Z, h^0\right), \nu(W^\pm, h^\pm)$	$l^\pm$	$l^\pm$
$\tilde{\chi}^\pm$	$h^\pm, W^\pm, \ell^\pm\nu$	$h^\pm, W^\pm$	$l^\pm\nu$	$h^\pm, W^\pm$
$\tilde{\nu}$	$\nu(1, h^0, Z), l^\pm(h^\mp W^\mp)$	$\nu\left(\gamma, Z, h^0\right), \ell^\pm(W^\mp, h^\mp)$	$l^\pm(h^\mp, W^\mp)$	$\nu(1, h^0, Z), l^\pm(h^\mp W^\mp)$
$\tilde{q}$	$j(1, h^0, Z, h^\pm, W^\pm)$	$j\left(\gamma, Z, h^0, W^\pm, h^\pm\right)$	$j(1, h^0, Z, h^\pm, W^\pm)$	$j(1, h^0, Z, h^\pm, W^\pm)$
$\tilde{g}$	$jj(1, h^0, Z, h^\pm, W^\pm)$	$jj\left(\gamma, Z, h^0, W^\pm, h^\pm\right)$	$jj(1, h^0, Z, h^\pm, W^\pm)$	$jj(1, h^0, Z, h^\pm, W^\pm)$

X' is R-Parity Odd

	$B^\alpha X'_\alpha$	$LH_u X'$ $LH_u X'^\dagger$	$LH_d^\dagger X'$ $LH_d^\dagger X'^\dagger$	$LLEX'$	$QDLX'$	$UDDX'$
$\tilde{\chi}^0$	h^0, Z, l^+l^-	$\nu(1, h^0, Z), l^\pm(h^\mp, W^\mp)$	$\nu(1, h^0, Z), l^\pm(h^\mp, W^\mp)$	$l^+l^-\nu$	$jj\,(l^\pm, \nu)$	jjj
$\tilde{l}^\pm$	$l^\pm$	$h^\pm, W^\pm$	$h^\pm, W^\pm$	$l^\pm\nu$	jj	$jjj\,(l^\pm, \nu)$
$\tilde{\chi}^\pm$	$h^\pm W^\pm$	$l^\pm$	$l^\pm$	$l^\pm l^+ l^-,\ l^\pm\nu\nu$	$jj\,(l^\pm, \nu)$	jjj
$\tilde{\nu}$	$\nu(1, h^0, Z), l^\pm(h^\mp W^\mp)$	h^0, Z	h^0, Z	l^+l^-	jj	$jjj\,(l^\pm, \nu)$
$\tilde{q}$	$j(1, h^0, Z, h^\pm, W^\pm)$	$j(l^\pm, \nu)$	$j(l^\pm, \nu)$	$j\,(l^+l^-\nu, l^\pm l^+ l^-, l^\pm\nu\nu)$	$j\,(l^\pm, \nu)$	jj
$\tilde{g}$	$jj(1, h^0, Z, h^\pm, W^\pm)$	$jj(l^\pm, \nu)$	$jj(l^\pm, \nu)$	$jj\,(l^+l^-\nu, l^\pm l^+ l^-, l^\pm\nu\nu)$	$jj\,(l^\pm, \nu)$	jjj

An Example: $\tilde{l}^{\pm} \to l^{\pm}\tilde{x}'$

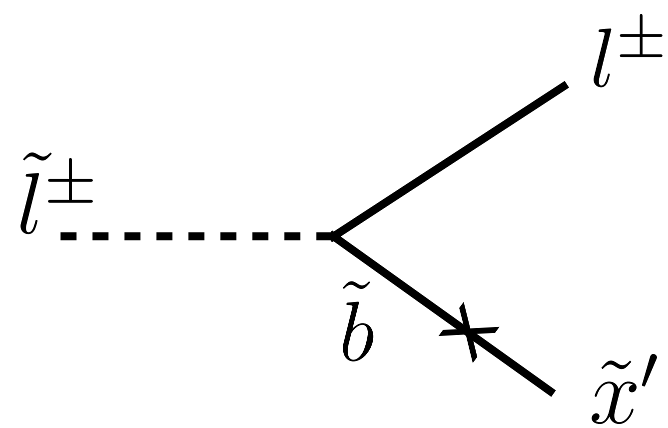
- Suppose LHC discovers a charged slepton LOSP with mass of 200GeV.
- Suppose slepton decays to lepton + missing energy.
- Suppose lifetime is measured to be 0.1sec, and m' is reconstructed to be 100GeV.

Production Mechanism:

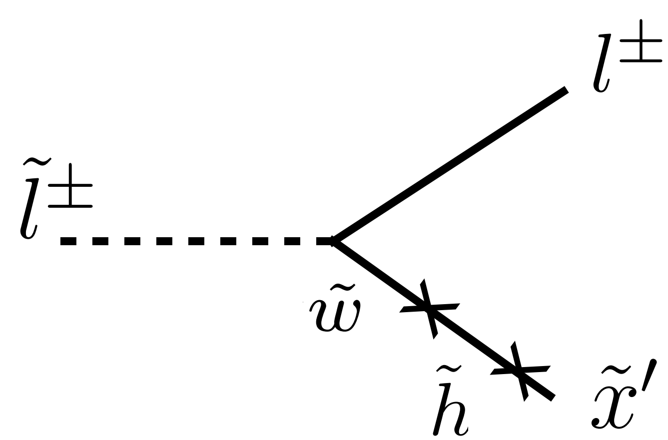
Low slepton mass → Cosmological Phase space chooses FI rather then FO&D

Portal:

- Bino Portal:



- Higgs Portal:



} Same signal but with different branching fraction.
Which portal?

To get correct relic abundance from FI: $\frac{m'}{m\tau}\left(\frac{100\ \mathrm{GeV}}{m}\right) = 25\ \mathrm{s}^{-1}$

So reconstructed lifetime 0.1sec is a factor of ten too big

→ Only 10% of DM abundance arises from FI of LOSP decays

Could other measurements reveal that the remaining 90% arose from FI of non-LOSPs?

Measure the superpartner spectrum:

- The Portal coupling can be extracted from the slepton lifetime and measurement of the neutralino mass matrix.
- Compute the yield of DM from FI from decays of other superpartners. These yeilds will differ for the Higgs and Bino portals.

→ Then we could see if the yield from non-LOSP decays in one of these portals accounts for the remaining 90% of DM.

Freeze-In

L. Hall, K. Jedamzik, J. March-Russel, S. West [0911.1120]

FI via decay of bath particle to the FIMP: $B_1 \to B_2 X$

$$\dot{n}_X + 3Hn_X = \int d\Pi_X d\Pi_{B_1} d\Pi_{B_2} (2\pi)^4 \delta^4(p_X + p_{B_2} - p_{B_1})$$
$$\times \left[|M|^2_{B_1 \to B_2 + X} f_{B_1}(1 \pm f_{B_2})(1 \pm f_X) - |M|^2_{B_2 + X \to B_1} f_{B_2} f_X (1 \pm f_{B_1}) \right]$$

$$\dot{n}_X + 3n_X H \approx g_{B_1} \int \frac{d^3 p_{B_1}}{(2\pi)^3} \frac{f_{B_1}\Gamma_{B_1}}{\gamma_{B_1}} = g_{B_1} \int_{m_{B_1}}^{\infty} \frac{m_{B_1}\Gamma_{B_1}}{2\pi^2} (E^2_{B_1} - m^2_{B_1})^{1/2} e^{-E_{B_1}/T} dE_{B_1}$$
$$= \frac{g_{B_1} m^2_{B_1} \Gamma_{B_1}}{2\pi^2} T K_1(m_{B_1}/T)$$

$$\boxed{Y_{1\to 2}(T) \propto \frac{M_{Pl}\, m_{B_1} \Gamma_{B_1}}{T^3}}$$

Bino Portal

X' is the gauge field of a U(1)' in the hidden sector:

$$\mathcal{L} = \lambda \int d^2\theta \, B^\alpha X'_\alpha + \tilde{\lambda} \int d^2\theta \, B^\alpha X'_\alpha \Phi \supset i\lambda \, \tilde{b}\bar{\sigma}^\mu \partial_\mu \tilde{x}' + \tilde{\lambda} \, m_{3/2} \, \tilde{b}\tilde{x}'$$

Coupling depends on UV theory and can be made small enough for FI

$$\lambda = \sum_i \frac{g_i g'_i}{16\pi^2} \mathrm{Log}\left(\frac{\Lambda}{m_i}\right)$$

Shift to remove gaugino kinetic mixing: $\tilde{B}_\alpha \to \tilde{B}_\alpha + \lambda \, \tilde{X}'_\alpha$

Hidden-Visible sector coupling induced in the interaction Lagrangian:

$$\begin{aligned} \mathcal{L}_{\mathrm{int}} &= \int d^4\theta \left(\Phi_i^\dagger e^{2g_i B_\alpha} \Phi_i + \Phi_j^{\dagger\prime} e^{2g'_j X'_\alpha} \Phi'_j\right) \\ &\to \left(\Phi_i^\dagger e^{2g_i (B_\alpha + \lambda \tilde{X}'_\alpha)} \Phi_i + \Phi_j^{\dagger\prime} e^{2g'_j X'_\alpha} \Phi'_j\right) \\ &\supset g_i \phi_i^\star \psi_i \tilde{b} + \mathrm{h.c} + g_i \lambda \, \phi_i^\star \psi_i \tilde{x}' + \ldots \end{aligned}$$

As well as mass mixing: $m_{\tilde{b}} \tilde{b}\tilde{b} \to m_{\tilde{b}} \tilde{b}\tilde{b} + \lambda m_{\tilde{b}} \left(\tilde{b}\tilde{x}' + \mathrm{h.c}\right)$

$$\boxed{\mathcal{L}_{\mathrm{int}} \approx \lambda \left(\tilde{x}' \tilde{J} + \tilde{b}\tilde{J}'\right)}$$

$\tilde{J}' = \sum_{\mathrm{i=hidden}} g'_i \phi'_i \psi'_i$

Detection at the LHC

Depends on the nature of the LOSP

Charged/Colored LOSP:

K. Hamaguchi, Y. Huno, T. Nakaya M. M. Nojiri hep-ph/0409248
J.L. Feng, B.T. Smith hep-ph/0409278 ...

- Lifetime and decay products can be measured for a large range of lifetimes 10^{-12} sec to 10^{-6} sec.
- Electrically charged sleptons and charginos will produce charge tracks which can be used to measure LOSP mass
- LOSPs emitted with small velocities will lose their kinetic energy by ionization and stop inside the calorimeter.
- Proposals for stopper detectors to be built outside the main detector.

Neutral LOSP:

- Prospects are highly dependent on LOSP lifetime
- For FI the lifetime~10^{-2}sec gives a decay length $L_{\rm FI} \sim 10^6 \text{ meters} \times \gamma \left(\frac{m'/m}{0.25}\right)\left(\frac{300\text{GeV}}{m}\right)\frac{1}{N_{\rm eff}}$